Modelling the potential impact of spatially targeted natural flood management at the landscape scale for a rural UK catchment.

PEARSON, CALLUM,JAMES

DURHAM UNIVERSITY

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MSc by Research

Callum James Pearson

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Abstract

Flooding has a significant impact across a large portion of the United Kingdom. Many flood risk reduction schemes focus on hard engineering approaches which are capable of protecting a large amount of infrastructure and properties. However, for a sparsely populated rural catchment that does not meet central cost-benefit criteria required for hard engineering schemes, the potential for a reduction in flood risk through a sustainable, lower-cost approach can create a viable alternative. Natural flood management is an approach that is growing in application in the UK with regards to helping reduce flood risk at a catchment scale; however there is a need for the potential impacts on flooding and wider catchment dynamics of the techniques and interventions to be quantified before potential schemes can attain funding; there is currently a lack of empirical evidence available to support this quantification.

This research project used a combination of a physically-based, fully spatially-distributed hydrological model (CRUM3), a risk-based model focused on hydrological connectivity (SCIMAP-Flood) and stakeholder engagement to develop and model natural flood management interventions at the landscape scale. The process allowed for the quantification of the impact of a variety of natural flood management interventions at reducing the maximum discharge for the simulated flooding event. These methods were applied to the study area of the River Roe catchment in Cumbria, a 69km^2 rural catchment that experienced significant flooding events in both 2005 and 2013.

The effectiveness of a variety of flood risk reduction scenarios in the River Roe catchment were tested; these scenarios included spatially targeted land cover change to attenuate overland flow, soil aeration to mitigate soil compaction issues commonly associated with rural catchments and woody debris dams to slow the delivery of water downstream. It was established through the research that a significant proportion of land has to be acted upon to have a noticeable reduction in the maximum discharge produced during a flood event; as a consequence of this finding, large-scale soil aeration to keep soil compaction to low levels throughout the catchment is arguably the most effective natural flood management measure for this catchment.

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I would like to thank the following people who have been there throughout the project:

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List of Abbreviations

AFPR	Absolute Flood Peak Ratio
Ara	Arable
BADC	British Atmospheric Data Centre
BGS	British Geological Survey
CEH	Centre for Ecology and Hydrology
ConW	Coniferous Woodland
CRUM	Connectivity of Runoff Model
CSA	Critical Source Area
DecW	Deciduous Woodland
DEFRA	Department for Agricultural Food and Rural Affairs
EU	European Union
FARM	Flood and Agricultural Risk Matrix
GLUE	Generalised Likelihood Uncertainty Estimation
hr	Hour
ImpG	Improved Grassland
K decay	Decay in saturated conductivity
Ksat	Saturated conductivity of the soil
LCM2007	Land Cover Map 2007
LNSE	Log Nash Sutcliffe Efficiency
LWD	Large Woody Debris
m	Metre
m^2	Square metre
m^3	Cubic metre
MaxQ	Maximum discharge
NatG	Natural Grassland
NERC	Natural Environment Research Council
NFM	Natural Flood Management
NSE	Nash Sutcliffe Efficiency
OS	Ordnance Survey
POST	Parliamentary Office of Science and Technology
Q	Discharge
Q01	Discharge exceeded 1% of the time
Q05	Discharge exceeded 5% of the time
Q95	Discharge exceeded 95% of the time
Q99	Discharge exceeded 99% of the time
RAFs	Runoff Attenuation Features
RCCWMG	Roe Catchment Community Water Management Group
s	Second
SCIMAP	Sensitive Catchment Integrated Modelling and Analysis Platform
SEPA	Scottish Environmental Protection Agency
SuDS	Sustainable Drainage System

UK	United Kingdom
Urb	Urban

1 Introduction

1.1 Aims and objectives

Flooding has a significant impact across a large portion of the United Kingdom and a large amount of research has been undertaken focusing on flood risk reduction solutions (Environment Agency, 2010). Flood risk throughout the UK results from a combination of a variety of sources with an estimated one in six homes located in an area at risk of fluvial or coastal flooding (Environment Agency, 2010). With an excess of £200 billion of property value at risk, flooding accounts for approximately £1 billion damage annually throughout the UK (Wilby et al., 2008; Hall et al., 2005).

Many flood risk reduction schemes have focused on hard engineering approaches which are capable of protecting a large amount of infrastructure and properties. However, for a sparsely populated rural catchment which does not meet central cost-benefit criteria required for hard engineering schemes, the potential for a reduction in flood risk through a sustainable, lower cost approach can create a great opportunity (Nisbet et al., 2011, Quinn et al., 2013). Natural flood management is an approach that is growing application and acceptance in the UK with regards to helping reduce flood risk at a catchment scale, however there is an understandable need for the impacts of techniques and interventions to be quantified before potential schemes can attain funding; there is currently a lack of empirical evidence available (POST, 2014). Additionally, despite increased usage of physically-based distributed models and research into the impact of land use change on hydrology, there is limited research into modelling the potential effects of flood risk reduction through catchment-based land management techniques and interventions. This research need has highlighted the opportunity for this project to contribute in a positive, original direction through the following overall aim:

To determine the effectiveness of catchment-based land management techniques and interventions at reducing flood risk in a rural UK catchment.

The objects for the project are:

1) **To engage and involve local stakeholders in the development of natural flood management intervention scenarios.**

The present day catchment management process has developed to involve a spectrum of stakeholders and not just government organisations. The use of Callon's (1999) co-production of knowledge model aims to empower all catchment stakeholders and incorporates local knowledge to help develop potential flood risk reduction solutions. Previous research, such as Howgate and Kenyon (2008) and Posthumus et al., (2008), has used stakeholder cooperation to help identify locations for the physical placement of natural flood management interventions; this project will use stakeholder participation and indigenous knowledge to shape flood risk scenarios to model.

2) **To determine if a spatially distributed hydrological model is suitable for investigating land management techniques and interventions for reducing flood risk.**

As evident in the literature review, there are several studies using distributed models to investigate land use change on a catchment scale; there is limited research available on the use of land management for flood risk reduction purposes. Also highlighted was the lack of options with regards to quantifying the impact of other natural flood management techniques and interventions for flood risk management on a catchment scale both in the field and in a hydrological model. A distributed model would allow spatial targeting of land use management and specific interventions whilst retaining a catchment scale approach.

3) **To quantify which land management techniques or interventions provide the greatest impact on reducing flood risk within a catchment.**

There is a variety of natural flood management techniques and interventions illustrated in the available literature that have an influence on catchment hydrology; this ranges from larger-scale land use management such as afforestation and soil aeration to individual features such as woody debris dams and retention/detention ponds. There is a need to quantify the impact these techniques and interventions can have on the discharge and thus which are best suited for flood risk mitigation. Consideration must also be given to the methods providing the best cost-benefit ratio as the failure to meet central funding criteria in many at-risk rural catchments was highlighted when conducting the literature review.

4) **To determine whether land management techniques and interventions can manage flood risk reduction without negatively influencing low flows.**

Whilst the project is predominantly concerned with flood risk reduction it is essential to determine that any potential technique or intervention implemented at a catchment scale does not negatively impact on existing low flow regimes in a catchment, which would have a significant impact on in-stream ecology. Any potential flood mitigation solution will have to consider both high and low flows.

1.2 Flood risk in the UK

A potential increase in the frequency and magnitude of fluvial flood events occurring in the UK due to anthropogenic induced climate change or natural climate variability will only enhance the issue (Robson, 2002). Current flood risk management in the UK involves structural measures (river engineering and flood defences) and non-structural measures (flood warnings, land use regulation and flood event response systems) (Posthumus et al., 2008).

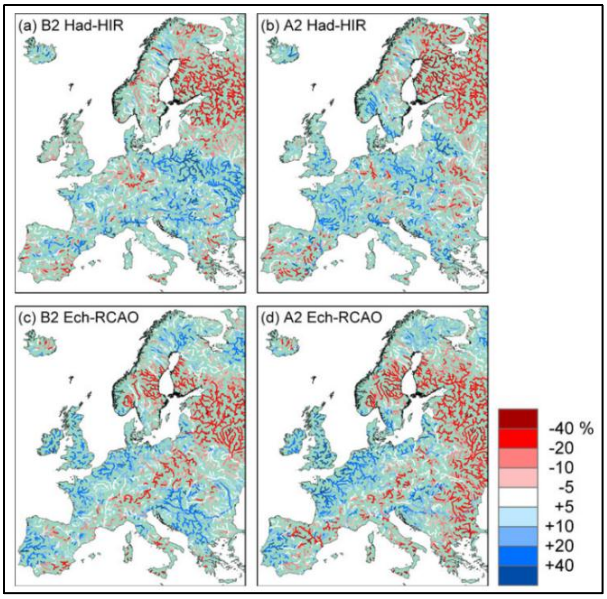

Figure 1.1 Relative change in 100-year return level of river discharge between scenario (2071–2100) and control period (1961–1990) for climate scenarios B2 Had-HIR (+2.5°C), A2 Had-HIR (+3.9°C), B2 Ech-RCAO (+4.1°C) and A2 Ech-RCAO (+5.4°C) (Feyen et al., 2012).

Hall et al. (2005) predict that by 2080 the annual damage could increase 20-fold if flood management policy, practice and investment levels remain in their present state. Figure 1.1 highlights the anticipated increase in a 100-year return period flow with only the least extreme climate change scenario seeing a reduced discharge between 2071 and 2100 in the United Kingdom (Feyen et al., 2012). Consequently Feyen et al. (2012) forecast a 2-fold increase in annual flood damage for the B2 Had-HIR scenario and an 8-fold increase for the A2 Ech-RCAO scenario. Future climate modelling results, as stated in Fowler and Kilsby (2007) and Kay et al. (2006), envisage a change in rainfall over the high latitudes of the Northern Hemisphere with the UK experiencing wetter winters and drier summers. This is expected to occur with an increased frequency and intensity of heavy rainfall events; by 2100 an event with a 50 year return period in the UK could experience an increase in magnitude of 30 percent (Fowler and Kilsby, 2007).

Trends in fluvial flooding are hard to detect; catchment-scale alterations to land use, storage, drainage schemes and flood alleviation schemes all impact on a flow regime in addition to climate change (Prudhomme et al., 2003). The predicted increase in flooding is supported with evidence determining an increase in the frequency and magnitude of high flow in the last 30 – 50 years in rivers in the UK. However establishing the cause is difficult with a limited range of data (Prudhomme et al., 2003; Robson, 2002). Identifying the land management alterations from climate induced changes in the hydrological record can be noticeably difficult (Lane, 2003). A longer period of data would help evaluate whether the increase is a long term trend or short term variability (Pattison, 2010). Significant flood events in 1998 (Easter Floods), 2000 (Sussex and Yorkshire), 2004 (Boscastle), 2005 (Carlisle), 2007 (Gloucestershire, Yorkshire and the Midlands), 2008 (Morpeth), 2009 (Cumbria) and 2012 (UK-wide) serve to provide recent examples of severe flooding to support this increasing trend (Environment Agency, 2010).

1.3 The impact of land use change and management on the hydrological regime in a rural catchment

1.3.1 Agricultural impact on catchment hydrology

Driven by UK and EU agricultural policy over the past 50 years there have been significant changes in UK land use and management practices (Figure 1.2) (O'Connell et al., 2007). Initiated by the 'plough-up campaign' in the 1940s the proportion of a given catchment under arable land use increased until the late 1990s (Crooks and Davies, 2001). Parry et al., (1992) ascertained that between 1945 and 1980 there was an increase of approximately 25% in cultivated land; correspondingly there was a decrease in deciduous woodland and both semi-natural and natural woodland. A shift in the preferred crop species can also impact surface runoff. Since 1978 the UK has seen an increase in the planting of maize, a crop sown in the early spring, and the low levels of plant coverage during the highest period of rainfall have meant low interception, low infiltration rates and increased overland flow (Boardman et al., 2009; Sullivan et al., 2004). Such land use change impacts on the hydrological processes within a catchment can modify both the evapotranspiration and surface runoff regimes. At a local scale there is evidence that surface runoff and flood generation has been enhanced by the modern management practices however the aggregation of local scale effects at larger scale is not evident (Fohrer et al., 2001; O'Connell et al., 2007). It must be noted that analysis of national trends has illustrated no significant impact of land use alteration at a catchment scale on flooding; this can be attributed in part to year-to-year climatic variation making trends difficult to identify (O'Connell et al., 2007; Lane, 2003).

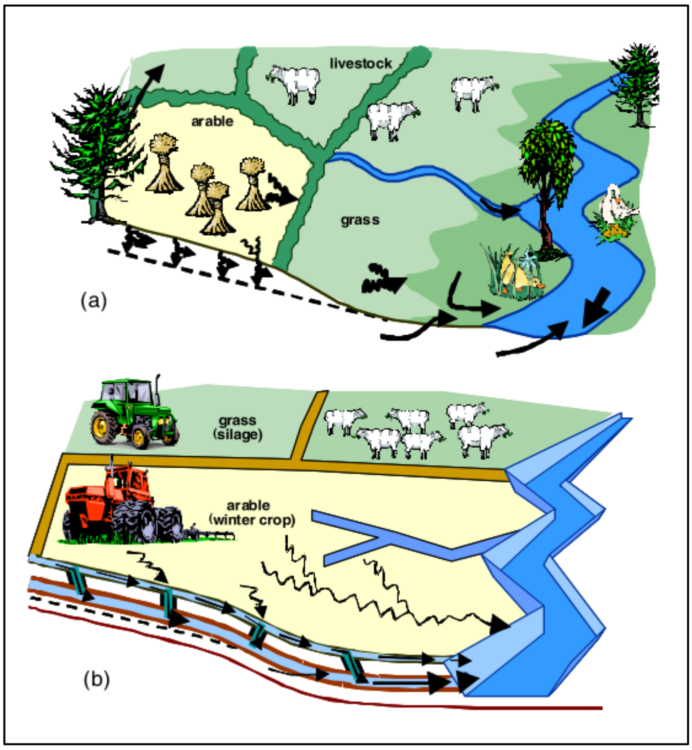

Figure 1.2 Pre-WW2 (a) and recent (b) agricultural landscapes at a hillslope scale (O'Connell et al., 2004)

The management of land to maximise agricultural output can change the hydrological properties of a catchment; this change has the potential to increase or decrease flood risk within a catchment (Kenyon et al., 2008). Kenyon et al. (2008) found that, when assessing agriculture as a cause of flood risk in Scotland, the intensification of agricultural practices enacted over the previous twenty years has increased downstream flood risk. Posthumus et al. (2008), having interviewed farmers and landowners in the Laver and Skell catchments in North Yorkshire, returned a range of land use factors that contributed to local flooding centred around infiltration and drainage and flow connectivity (Figure 1.3). The loss of natural flood storage areas through the drainage of ponds, natural wetlands and upland areas and the increased reaction to runoff through the straightening and canalisation of burns were seen as the primary reasons behind the increased risk (Kenyon et al., 2008). O'Connell et al., (2007) and Posthumus et al., (2008) summarise other post-WWII changes that many British agricultural catchments have undergone; the rapid loss of hedgerows and consequently the creation of larger fields have connected once disconnected runoff pathways, altered cultivation practices causing increased soil compaction, plough lines and farm tracks focusing overland flow and increased hydrological connectivity with land drains. All these factors have the potential to increase runoff generation and reduce infiltration. The probability of runoff generation due to land management practices has been conceptualised in the Flood and Agriculture Risk Matrix

(FARM) (see Figure 1.4); it captures the likelihood of existing agricultural land practices generating run-off (Posthumus et al., 2008; Wilkinson et al., 2013).

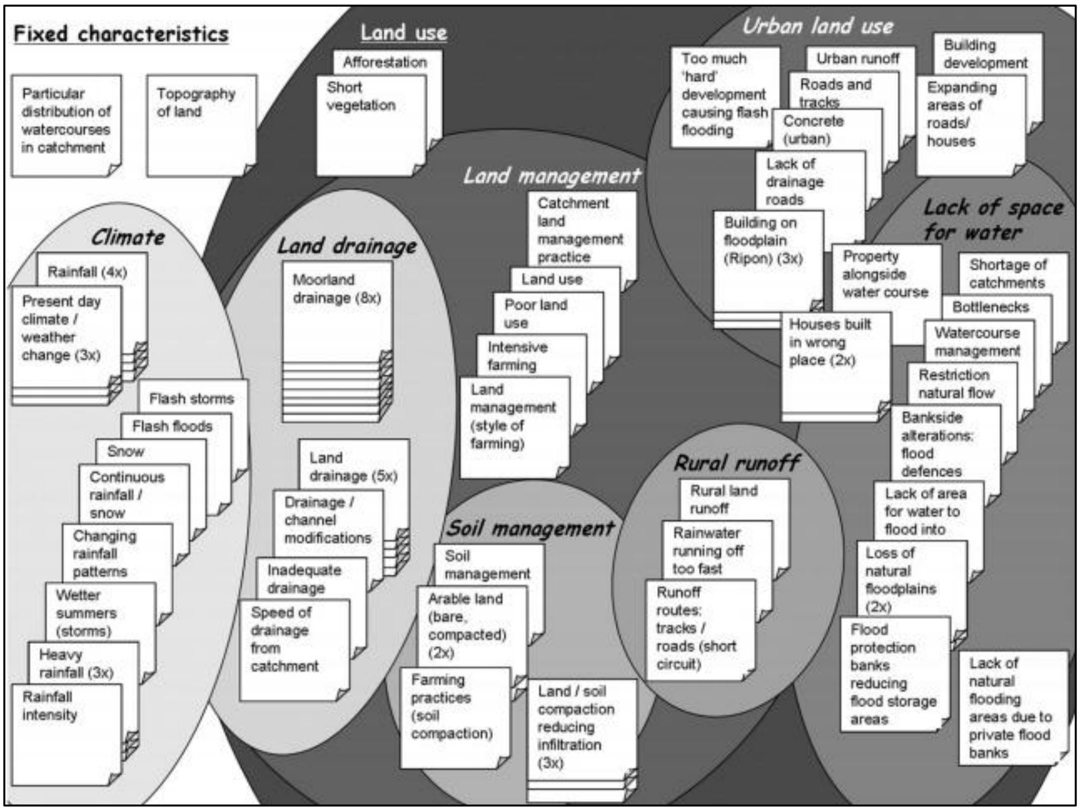

Figure 1.3 Factors contributing to flooding in Ripon, North Yorkshire as taken from a stakeholder workshop (Posthumus et al., 2008).

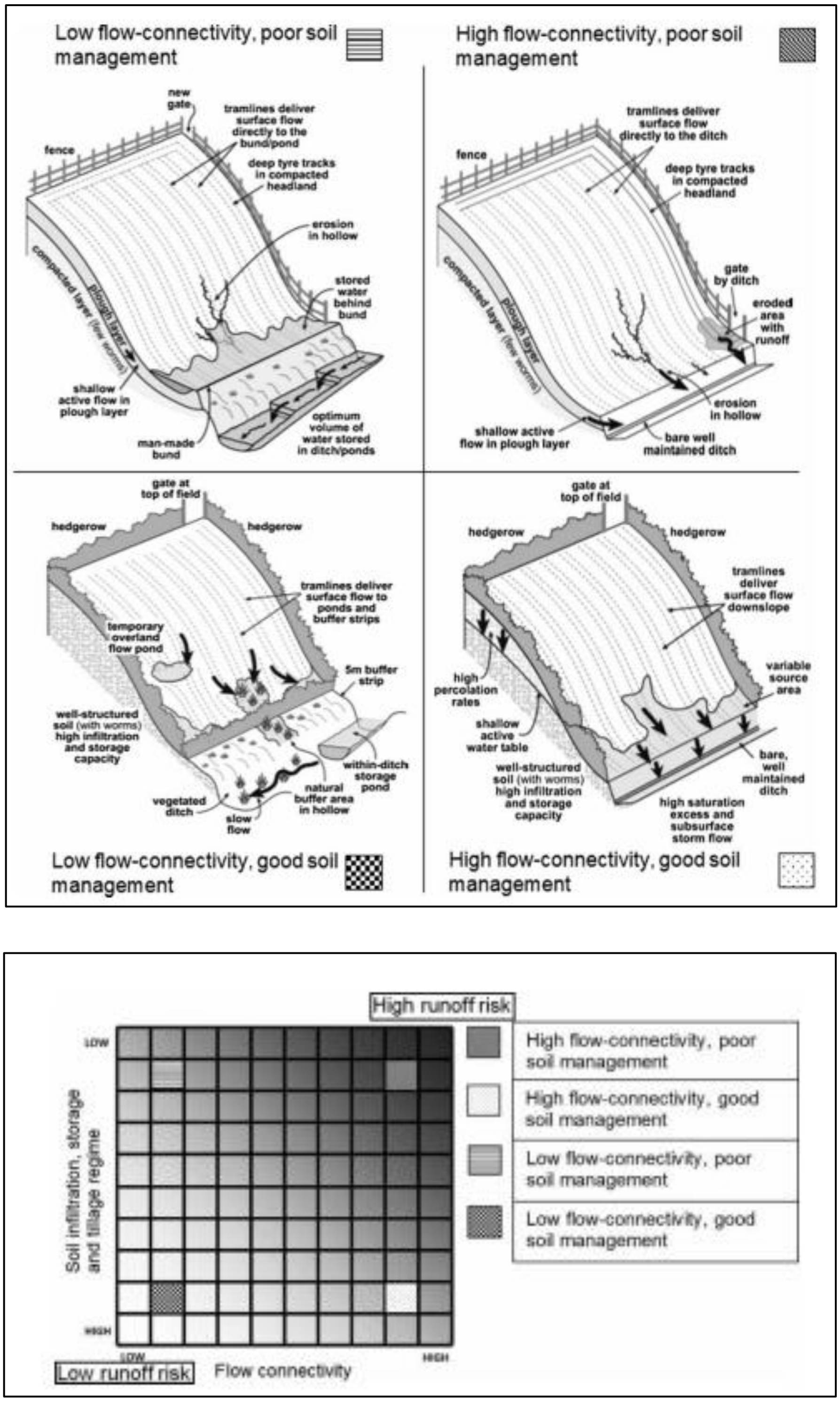

Figure 1.4 Four hillslope runoff scenarios for the same land unit (top) and the scenarios mapped on the FARM decision support matrix (bottom) (Wilkinson et al., 2013).

1.3.2 The impact of vegetation change on soil properties

Vegetation change affects the interception storage and litter storage, which consequently impacts upon the evapotranspiration balance and the infiltration excess overland flow regime (Bronstert et al., 2002). Investigating land use change on an artificial catchment Fohrer et al. (2001) found that the introduction of pasture to a once forested area reduced the evapotranspiration rate by 19% whilst the introduction of barley witnessed a reduction of 31%; the lower figure from the barley can be attributed to a shorter vegetation period. The research also quantified surface runoff and established that there was a 180% increase in the runoff between barley and forest; correspondingly river flow also increased due to lower interception rates of barley (Fohrer et al., 2001). Brown et al. (2005) summarised the research into the impact of deforestation, afforestation and forest conversion (altering the existing forest type) on the mean annual water yield using paired catchment studies. The reduction of forest cover in temperate zones, evident in Hewlett and Hibbert (1967) and Bosch and Hewlett (1982), causes an increase in catchment water yield whilst increasing coverage causes a decrease in water yield. In the 94 paired catchments Bosch and Hewlett (1982) determined a decrease in water yield that was most influenced by coniferous forest (~40mm decrease per 10% coverage), followed by deciduous woodland (~25mm) and then shrub and grassland (~10mm). In a UK context Marc and Robinson (2007) used the Severn and Wye catchments to establish that annual water loss from evaporation in a fully forested catchment would result in an 18% decrease in annual flow from a grassland upland catchment. The factor of 1.8 from grassland to forest evaporation rate corresponds to the factor of 2 found in research undertaken by Calder (1976) on the Hore catchment; Calder (1976) concludes that the annual actual evaporation rate of forest cover is 900mm in comparison to 440mm for short grassland. Additionally comparing the Severn and Wye catchments Robinson and Dupeyrat (2005) state that catchment deforestation shows a notable increase in low flows but no detectable change in flood peaks; the greatest alteration to the flow regime occurred when large areas of woodland were felled in a single year.

1.3.3 Soil Compaction

Compaction alters the structure of the soil by increasing the bulk density, disintegrating soil aggregates and decreasing soil porosity, aeration and infiltration capacity (Figure 1.5) (Kozlowski, 1999). Soil compaction resulting from changes in grazing patterns, increased livestock densities, and the usage of heavier machinery impacts the hydrological regime (Wheater, 2002). The usage of heavy machinery during ploughing, both on wheels or tracks, can decrease the hydraulic conductivity of soil by up to 40%; this is dependent on vehicular and load weight and soil characteristics (Coutadeur et al., 2002; Pattison and Lane, 2011). Servadio et al. (2001) establish that on clay dominated soil one pass from wheeled machinery could reduce soil hydraulic conductivity from 18.5mm hr^{-1} to 3.3mm hr^{-1}, whilst vehicles with tracks saw a reduction to 11.2mm hr^{-1}. Four passes saw a corresponding reduction to 1.1mm hr^{-1} and 7.5mm hr^{-1} (Servadio et al., 2001). Thus the impact of machinery in causing soil compaction can be mitigated with the use of low-pressure tyres and rubber tracks; the latter compacting the topsoil but creating less deep compaction than wheels

(Boguzas and Hakansson, 2001; Febo and Planeta, 2000). Reed (1983) established that surface runoff from vehicular compaction increased by 11% to 13%. Additionally the seasonality of ploughing can produce a 30% to 100% reduction in runoff generation, with spring and autumn ploughing causing less runoff than winter ploughing (Kwaad and Mulligan, 1991).

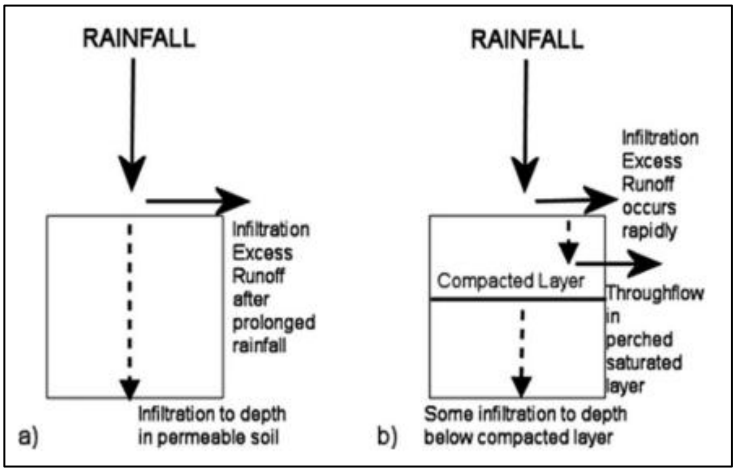

Figure 1.5 Schematic illustrating the effects of compaction on soil infiltration (Pattison and Lane, 2011)

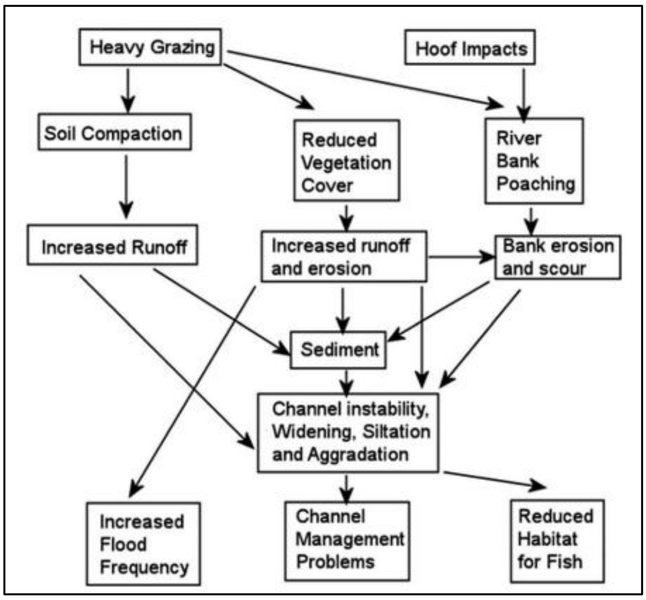

Figure 1.6 Impacts of overgrazing on runoff and soil erosion (Pattison and Lane, 2011)

The extent of soil compaction caused by livestock is dependent on the species, pasture cover, stocking density and grazing duration in addition to the prevalent soil conditions and topography (Figure 1.6) (Nguyen et al., 1998; Pattison and Lane, 2011). Globally stocking density has been increasing as grazing moves to an intensive continuous year-long cycle (Warren et al., 1986). Fuller and Gough (1999) highlighted that in the UK there were 8 million sheep in 1860, 19.7 million in 1950 and 40.2 million in 1990. The UK cattle population has also increased with 6 million in 1875 in comparison to 9.8 million in 2015 (Bolton et al., 2015). Cattle and sheep differ in their causation of soil compaction with cattle disturbing the soil through upward and downward movement whilst sheep cause surface compaction (Betteridge et al., 1999). Rauzi and Smith (1973) found that a lightly grazed plot has infiltration rates of 59mm hr^{-1} in comparison to a moderately (56mm hr^{-1}) and a highly grazed plot (48mm hr^{-1}). Evans (1996) and Orr and Carling (2006) found that the increase in sheep numbers in both the River Derwent and upper River Lune catchments coincided with increased runoff rates and greater flood peaks; the doubling of sheep numbers in the Derwent catchment saw in an increase in runoff of 25%. The increased density of livestock reduces plant biomass and consequently lowers evapotranspiration rates through overgrazing (Pattison and Lane, 2011). The reduction in vegetation coverage through overgrazing can additionally reduce the resistance of the surface to overland flow (Ferrero, 1991). Heathwaite et al. (1989) suggest that 53% of rainfall was converted to runoff in a grazed field in comparison to 7% in an ungrazed field due to a reduction in infiltration capacity of 80% in the grazed areas.

1.4 Hydrological connectivity

Connectivity is considered a relatively recent concept in hydrology and a fully encompassing definition of hydrological connectivity remains under debate (Bracken et al., 2013; Shore et al., 2013). Yang and Chu (2013) state that hydrological connectivity represents the spatio-temporal conveyance passage to transfer water and associated mass over a landscape. However there are commonly accepted key aspects of hydrological connectivity; the spatial distribution of connected zones such as saturated areas and frequency and magnitude of the connections (Wainwright et al., 2010). Bracken and Croke (2007) cite five major components that make up hydrological connectivity within a catchment; climate, hillslope runoff potential (slope), landscape position, delivery pathway and lateral buffering (Bracken and Croke, 2007). Climate has a vital control on the runoff regime and determines the duration, intensity and distribution of precipitation; along with a non-uniform response to rainfall due to other connectivity components (e.g. vegetation and infiltration capacity) throughout the catchment there is much spatial variation (Bracken and Croke, 2007). Occurring over a variety of scales hydrological connectivity is a dynamic, evolving process with increasing rainfall intensity and duration altering pathways; this is evident on a small scale in Figure 1.7 as the number of connected areas increase with increased rainfall input (Yang and Chu, 2013). Investigation and analysis of hydrological connectivity throughout the catchment can identify areas of high and low connectivity; prior models, indices and field studies investigating connectivity are in outlined in Bracken et al., (2013). Reaney et al. (2011) used a spatial index of relative hydrological connectivity within the SCIMAP approach. This approach was able to identify the pattern of possible connections at the landscape scale. The approach was tested against spatial patterns of salmon numbers impacted by fine sediment and in Milledge et al. (2012), against nitrogen and phosphorus levels, both of which should co-vary with flood risk due to the reliance on rapid surface pathways. The spatial identification of highly connected areas can be utilised in flood management; notably by ensuring the effectiveness of flood risk reduction measures which attempt to reduce the connectivity of a pathway.

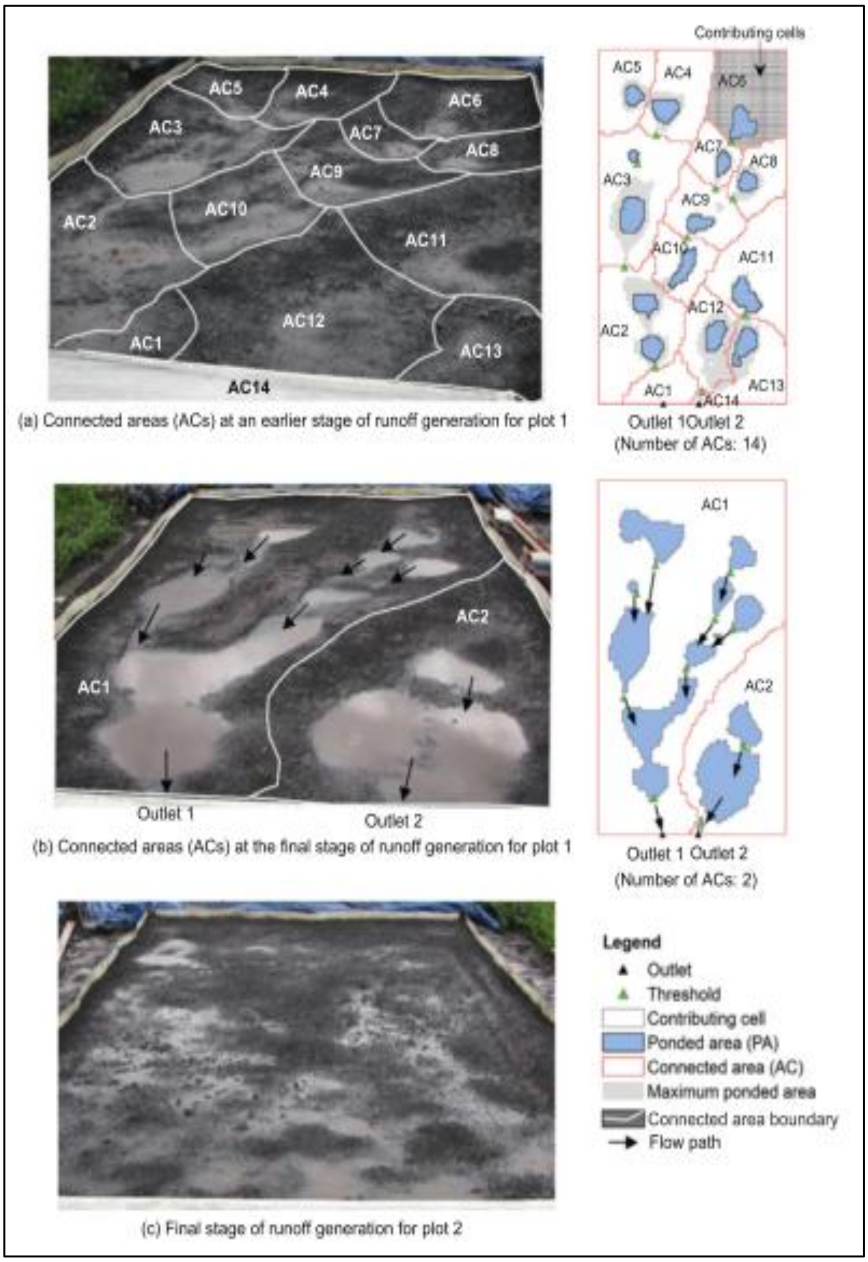

Figure 1.7 Dynamic puddle filling-spilling processes and evolution/formation of hydrologically connected areas (taken from Yang and Chu, 2013).

1.5 Catchment-based management to reduce flood risk

Investment in flood defences has been dominated by a paradigm of hard engineering solutions (Thorne et al., 2007); this approach has protected urban areas from inundation and enabled the cultivation and grazing in field's right up to the edge of the river (Howgate and Kenyon, 2009). The cost of implementation and maintenance of the concrete defences coupled with limited budgets and increasing flood risk throughout much of the UK, has led to need to a focus on more sustainable, cheaper, flood management on a catchment-wide scale (Nisbet et al., 2011). The Water Framework Directive (2000/60/EC), Defra's Water Strategy, the European Floods Directive (2007/60/EC) and Making Space For Water (Defra, 2005) provide the framework to drive sustainable flood management in the UK (Parrott et al., 2009). Flood protection policy in the UK is progressing towards the promotion of holistic flood management within catchments; incorporating traditional structural defences while seeking to work with natural processes to reduce flood risk (Howgate and Kenyon, 2009; Nisbet et al., 2011). However, there is a lack of empirical evidence due to the difficulty of quantifying the effectiveness of natural flood management and this information gap is inhibiting the uptake with many schemes proposed in the UK struggling to meet criteria for cost-benefit analysis based funding (POST, 2014). The Pitt Report (Pitt, 2008) identified three general types of catchment management solutions to reduce flood risk in a rural catchment (Environment Agency, 2010): 1, water retention through infiltration management, 2, water retention through catchment storage schemes and 3, conveyance management; each will be briefly explored in the following paragraphs. The location and spatial distribution of these natural flood management solutions within the aforementioned themes is evident in Figure 1.8. Many of the measures discussed below have benefits outside of purely flood risk reduction; offering improved pollution control, reduced soil erosion, increased biodiversity and water quality and potentially an enhanced value as an amenity (Thorne et al., 2007). Technical information on individual techniques and interventions is explored further in Environment Agency (2011), Quinn et al. (2013), Nicholson et al. (2012) and Environment Agency (2012). Notable projects in the UK investigating natural flood management techniques and interventions can be found on the Belford catchment (Wilkinson et al., 2010), Pontbren catchment (Wheater et al., 2008), Hodder catchment (O'Donnell et al., 2011), Pickering catchment (Forestry Commission, 2004) and the Parrett catchment (Morris et al., 2008).

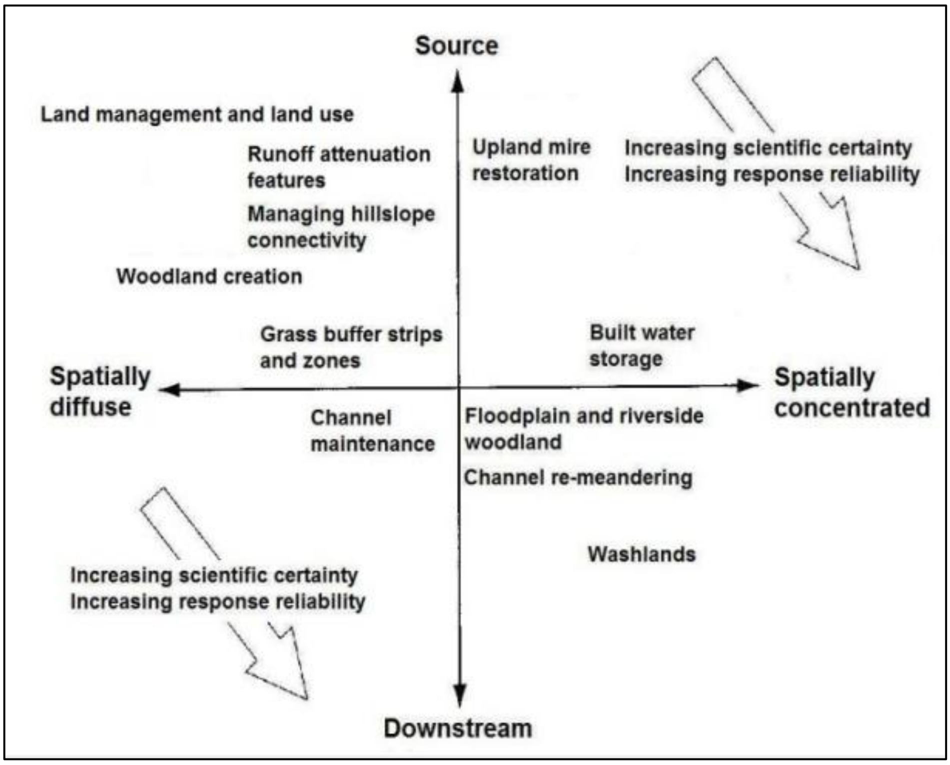

Figure 1.8 A catchment-scale classification of natural flood management strategies (POST, 2011).

1.5.1 Infiltration management

Managing infiltration within a catchment has the potential to reduce flood risk at a variety of scales; many of the practices have a noticeable effect at a local or field scale and would need to be replicated throughout the catchment to have an influence on flood risk (Thorne et al., 2007). Changes in arable land use practices and livestock management can reduce runoff at a field scale; techniques include altering tillage regimes, using cover crops, livestock rotation and reducing livestock density (Thorne et al., 2007). Owens et al. (1997) state that restricting livestock to summer grazing can reduce a catchments percentage runoff by 8% annually. Soil aeration and subsoiling can reduce surface compaction by increasing the size and number of macropores in the soil and thus enhancing the infiltration capacity (Douglas et al., 1998; Pikul and Aase, 2003). Buffer strips and buffering zones, areas of uncultivated land that intercept pathways of concentrated runoff, reduce runoff generation through an increased infiltration capacity in the soil (Pattison, 2010). An understanding of the hydrological connectivity at the intended site is vital for the buffer area to be useful and effectiveness of the zones or strips reduces as rainfall duration increases as the soil becomes saturated (Thorne et al., 2007). Afforestation, as with buffer areas, decreases overland flow through enhances local infiltration and increased evapotranspiration and interception loss rates (Thorne et al., 2007). Tree planting increases the saturated conductivity of the soil resulting in less overland flow and greater throughflow (Pattison and Lane, 2011). Whilst dependent on climate and tree species up to 30% of rainfall intercepted in the canopy is lost through evapotranspiration (Johnson, 1998). Fohrer et al. (2001) state that the most important effect of afforestation is the increased water storage delaying potential runoff. Salazar et al. (2012) modelled the impact of altering existing agricultural land to forest in three European catchments and found a one-third reduction in peak flow during small storm events but almost no difference in a larger magnitude event. Finally Thorne et al. (2007) evidence that, in the short term, the preparation towards and undertaking of afforestation can increase local flood risk until the stand has properly developed; during research on the Coalburn catchment peak flows increased by 20% for the first 5 years of forest planting (Robinson, 1986).

1.5.2 Storage of water

The storage of water throughout the catchment can impact on the flood regime and with numerous off-line and on-line storage measures in place the cumulative effect can have a catchment-wide impact on flood risk (Thorne et al., 2007). Off-line features store flood water in ponds adjacent to the river whilst on-line features store water on the course of the river (Environment Agency, 2011). Increasingly agricultural best practice guidelines are making reference to Sustainable Drainage Systems (SuDS) to be implemented at a farm scale; in a rural catchment much of this storage required to reduce flood risk can be created in the farming landscape with the use of runoff attenuation features (RAFs) (Environment Agency, 2010; Environment Agency, 2012). RAFs aim to regulate the quantity of water that reaches the water course, lowering and elongating the flood peak. RAFs can take a variety of forms from retention/detention ponds to woody debris dams to bunds and barriers within ditches; Figure 1.9 and 1.10 illustrate how RAFs react during a storm event (Environment Agency, 2012).

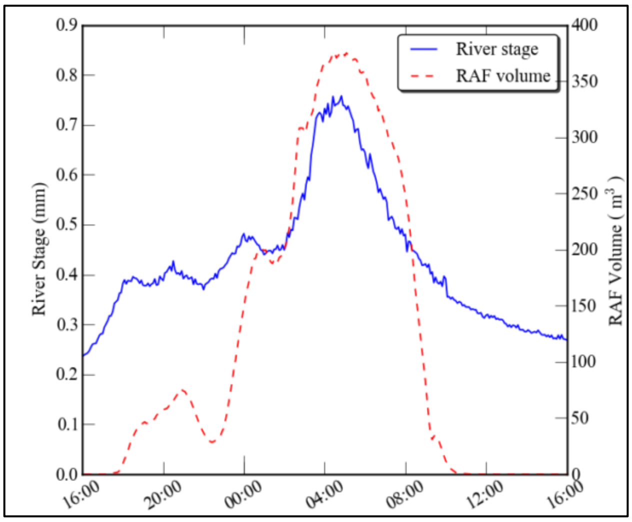

Figure 1.9 A graph from Quinn et al. (2013) illustrating how a RAF temporarily stores water during a storm event.

Figure 1.10 Examples of RAFs from Environment Agency (2011). A field bund temporarily storing overland flow during a storm event (top), a large woody debris dam (middle) and an offline storage pond constructed with a timber barrier (bottom).

Individual RAFs often have limited impact on the flood peak and require a network of features to have a positive influence on flood risk (Quinn et al., 2013). On a larger scale Thorne et al. (2007) cite the use of impounding the flow, reservoir creation and permanent flow regulation as flood risk reduction methods; the permanence and significance of the land use change have a profound influence on the catchment characteristics. Finally wetland creation/restoration can help decrease flood risk through intercepting runoff and temporarily retaining water; the retained surface water experiences loss through evaporation (Pattison, 2010). The location, size and level of control over inflow and outflow vary the influence of a wetland on flood risk.

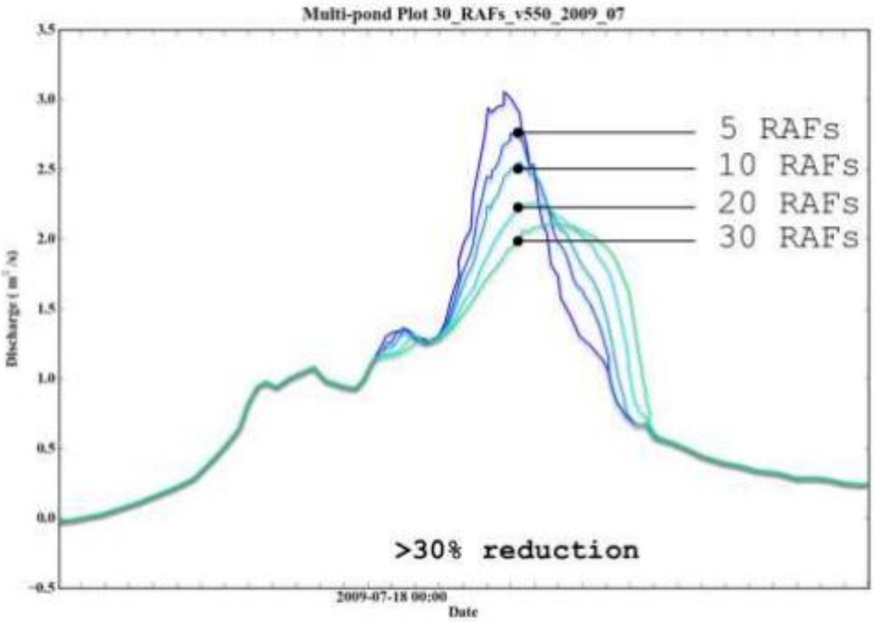

Figure 1.11 A hypothetical hydrograph highlighting the cumulative effect of a network of storage ponds on a catchment. It is clear that the peak is delayed, reduced and elongated as the number of ponds increases (Nicholson and Iacob, 2015).

1.5.3 Managing conveyance

Management of hillslope and river channel conveyance can make an impression on the flood regime in a catchment (Thorne et al., 2007). Hillslope conveyance can be altered by reversing conventional land management practices often already in place; the removal of land drains slows the pathway of water through a field and reinstating hedgerows can reduce the strength of the hydrological connectivity of a field (Paningbatan et al., 1995; Thorne et al., 2007). Schwab et al. (1993) quantified the effect of contour ploughing on the conveyance of in-field runoff with up to an 80% runoff reduction. With a recent bias towards hard engineering the restoration of flood plains and the natural channel morphology influences the transferal of flood water through the system. Acreman et al. (2003) modelled scenarios for flood risk for the River Cherwell, UK and concluded that embanking the river created flashier flood and peak flows with an increase of 50% to 150% on present levels. The increase was due to the disconnection of the floodplains and the associated reduction in storage with increased transportation speed for flood water through the network (Acreman et al., 2003). The restoration of the river to a pre-1900 condition in a second scenario saw a reduction of 10% to 15% in peak flow and an elongated flood hydrograph. The decreased channel capacity meant more flood water was stored on the connected flood plains and any flow was slowed with greater surface roughness (Acreman et al., 2003). Improved in-channel vegetation also increases surface roughness and flow resistance; lessening flood risk (Thorne et al., 2007).

1.6 The use of hydrological models to assess flood risk reduction through catchment-based land management techniques and interventions

Hydrological models have an extensive range of applications including water resource management, flood risk management and climate change prediction (Pechlivanidis et al., 2011). Models can help develop greater understanding of the hydrological system and allow the extrapolation of both time and space; assisting the identification of dominant processes involved and the assessment of the impact of change (Singh and Woolhiser, 2002). Modelling provides a method of investigating and quantifying changes of a catchments hydrological regime through land use alteration without having to physically alter the existing land cover to measure change (Mulligan, 2004).

Models structures range from simple 'black box' representations of input and output to complex representations of the spatio-temporal complexity of catchments (Mulligan, 2004). As outlined by Wheater et al. (1993) models can be classified by their structure, spatial distribution and stochasticity. Metric or empirical models are predominantly based on observations and use the available data to characterise the response of the hydrological system; the Flood Estimation Handbook is an example of an empirical model with physical and climatic descriptors applied to relating model properties (percentage runoff and unit hydrograph time to peak for example) (Pechlivanidis et al., 2011). Conceptual models, as stated by Wheater (2002), vary in complexity but tend to represent the component system processes seeming to be of importance in catchment scale input-output relationships; not all parameters are independently measured and have a direct relationship interpretation. Physically based models use continuum mechanics to represent hydrological processes including evapotranspiration and infiltration; the model is defined by measurable parameters and the physics behind the structure generally stems from laboratory or in-situ field experiments (Pechlivanidis et al., 2011). Beven (2004) notes that extrapolation of these processes to larger scales involves the assumption that the processes and properties are independent of scale. Wagener (2007) noted that whilst models can be categorised, many hydrological models are hybrid models including elements of two or more of the above with many physical-based models simplifying mathematical processes in a conceptual manner. In addition to their spatial structure models can be classified as lumped, semi-distributed or distributed with regards to spatial distribution of the process representation. Lumped models, such as the aforementioned Flood Estimation Handbook, average variables over the catchment area handling the catchment as a singular unit; they do not take into account the spatial variability of processes across the landscape (Beven, 2001). Distributed models spatially distribute variables throughout the catchment using structures such as grid squares and solve equations for each variable within each location; these models take into consideration spatial variability for the hydrological processes within the catchment (Singh and Frevert, 2006). Commonly used examples of distributed models are MIKE SHE (DHI, 1999), SHETRAN (Ewen and Parkin, 1996), THALES (Grayson et al, 1992) and DHSVM (Thanapakpawin et al., 2007). Finally semi-distributed models are a compromise between the fully distributed and lumped representations; the catchment is divided into smaller useful lumped models rather than a spatial continuous grid (Pechlivanidis et al., 2011). SWAT is a popular example of a semi-distributed model (Gassman et al., 2007).

Increased availability of powerful computer resources, fine-scale spatially distributed datasets and information on the physical properties of a catchment has witnessed an uptake in the usage of distributed models (Pechlivanidis et al., 2011; Blöschl et al., 2008). The increased integration of land and water management has led to a variety of research investigating the hydrological response to land use alteration in a catchment using distributed models; they have the predictive capacity to assess land use change on runoff across a range of spatial scales (Beven, 1989). Recent studies, for example, have been completed assessing the impact of land use change derived from forecasted population growth on catchment hydrology (Thanapakpawin et al., 2007; Wijesekara et al., 2012), the impact on sediment yield and erosion risk (Alatorre et al., 2012; Tang et al., 2011), stream ecology (Guse et al., 2015), streamflow (Im et al., 2009; Oogathoo, 2006) and the impact on hydrologic processes in relation to future climate change (DeFries and Eshleman, 2004; Bronstert, 2004). With regards to modelling land use change and flood management, spatially distributed models have predominantly been used to investigate the impact of catchment-scale afforestation (Fohrer et al., (2001); Gebremeskel et al., (2005); Bronstert et al., (2007); Salazar et al., (2012); Calder et al., 2003); De Roo et al., 2001)). Jackson et al. (2008) model the impact of upland management on flooding. In addition to spatial targeted afforestation Salazar et al. (2012) modelled the effectiveness of micro-ponds and small reservoirs to retain water in the landscape; it must be noted, however, there is minimal literature on the distributed modelling of land management for flood risk reduction purposes and less still on the effectiveness of natural flood management techniques and interventions.

1.7 Stakeholder engagement

The approach to managing flood risk throughout the UK has changed significantly over time and is now a multidisciplinary approach (Foundation for Water Research, 2015). Originally flood risk management, in addition to other issues in the wider environment, was centrally controlled through organisation such as the Environment Agency, Scottish Environmental Protection Agency, the Lead Local Flood Authority, Highways Agency and local district council; the decision making was delivered 'linearly' by the experts to the community (Callon, 1999; Lane et al., 2011; Foundation for Water Research, 2015). Whilst not statutorily accountable, there is increasing involvement from a range of local groups and organisations; examples include rivers and wildlife trusts, national park authorities and local community groups (Foundation for Water Research, 2015). This altered stakeholder involvement has created a network of catchment partnerships illustrated in Figure 1.12.

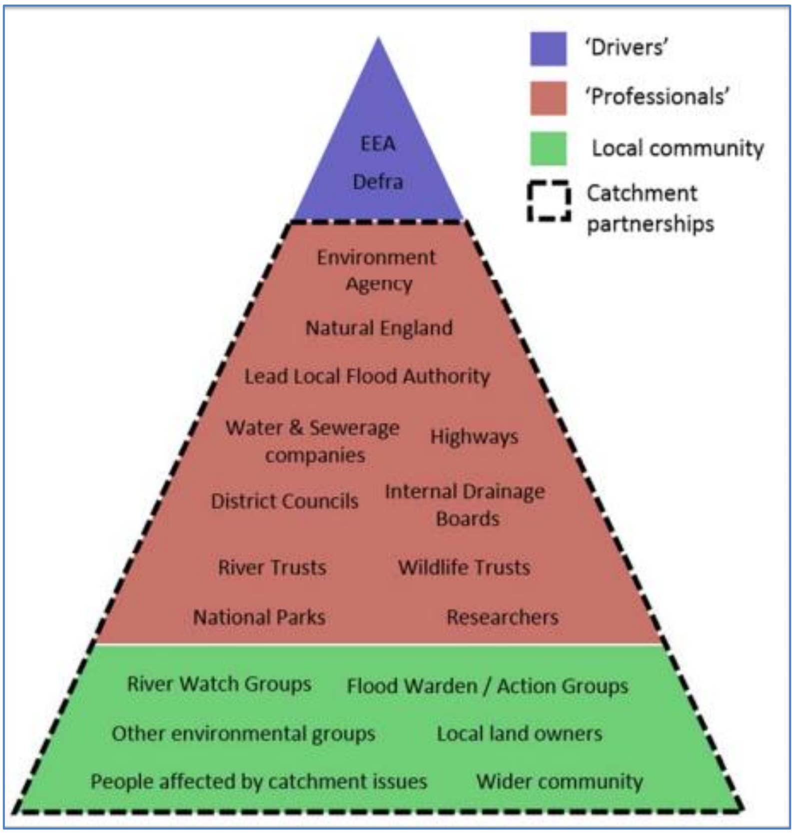

Figure 1.12 Stakeholders involved in the modern day catchment management and restoration process (Foundation for Water Research, 2015).

There has been a shift in scientific practice towards the integration of this indigenous knowledge and the possibility to incorporate this valuable local information into specialist analysis tools and provide appropriate solutions to flood risk issues (Lane et al., 2011). The inclusive nature of public experience allows a co-production of knowledge; a model of risk communication offered by Callon (1999). The final approach of the Callon (1999) three stakeholder participation combinations, as outlined in Figure 1.13, allows the empowerment of all involved parties and the creation of locally aware and scientifically suitable flood risk reduction scenarios.

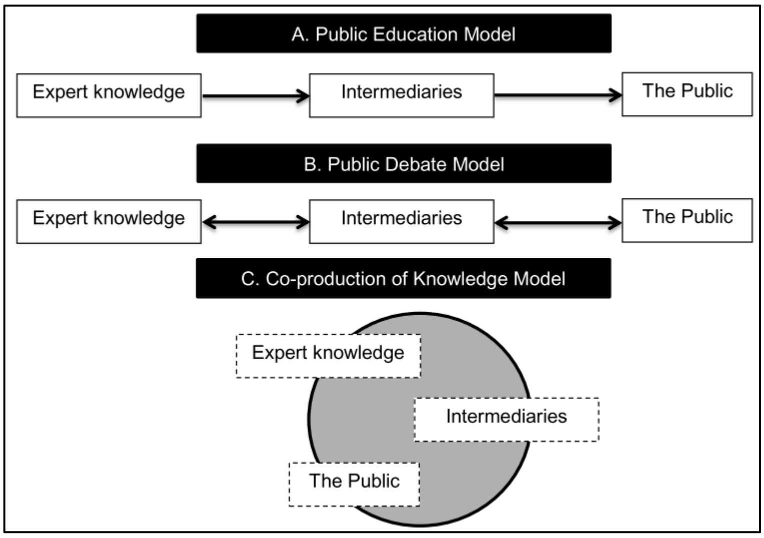

Figure 1.13 Models of risk communication in Callon (1999). Taken from Marshfield (2014).

There are numerous UK examples of stakeholder engagement in catchment management schemes. Stakeholder participation has been utilised in catchment planning on the River Dee (Mostert et al., 2007), River Tame (Petts, 2007), River Ribble (Carter and Howe, 2006) and River Argyll, Clyde and Tweed (Blackstock et al., 2012). Case studies using stakeholder cooperation for natural flood management implementation are on the River Devon and Tarland (Howgate and Kenyon, 2009), Pickering (Lane et al., 2011), Bowmont (Wilkinson et al., 2014) and Belford (Wilkinson et al., 2010). These studies showed the added value of local stakeholders in the knowledge production process with contributions in the collation, processing and sharing of information.

1.8 Thesis Structure

This chapter has illustrated the requirement for natural flood management techniques and interventions to be quantified using a distributed model. Chapter 2 explores the characteristics of the study catchment; outlining climate, geomorphology, geology and land use. Chapter 3 then outlines the methods employed to fulfil the aforementioned research aims. Chapter 4 assesses the capability of a distributed model to model flood events whilst accounting for land cover, the findings of the stakeholder engagement and the results from the modelled flood risk reduction scenarios. Finally, chapter 5 presents the discussion of the project results and the conclusion.

2 The River Roe Catchment

This chapter examines the characteristics of the River Roe catchment by introducing its location (section 2.1) within the UK and the wider River Eden catchment, catchment characteristics (section 2.2), historical and present land cover (section 2.3) and the stakeholders involved in the project (section 2.4).

The River Roe catchment was chosen as the study site for this project due to its catchment characteristics and flood history. The River Roe catchment has a rural landscape with a dispersed population and has experienced two recent large flash flood events (2005 and 2013) which caused considerable property damage around the villages of Highbridge and principally Stockdalewath. The community failed to meet the central funding criteria for a flood risk reduction scheme due to the rural nature of the catchment and low population. Additionally the catchment has an active community that, through the creation of the Roe Catchment Community Water Management Group (RCCWMG), have a desire to solve the future flooding problems with natural flood management techniques and interventions. Similar research on land management and using the CRUM3 model has been carried out in the wider River Eden Catchment (Pattison, 2010) and nearby Dacre Beck (Baugh, 2010; Smith, 2011).

2.1 Location

Located in the north east of Cumbria, the River Roe catchment is a 69km^2 sub-catchment of the River Caldew and ultimately the River Eden (Figure 2.1). It is situated north of the Lake District National Park (LDNP) and 11km south of Carlisle. The River Roe catchment contains a small population with the majority of properties in the two villages of Stockdalewath and Ivegill; Land Cover Map 2007 (CEH, 2015) ascertain that 0.32% of the catchment is urban or suburban.

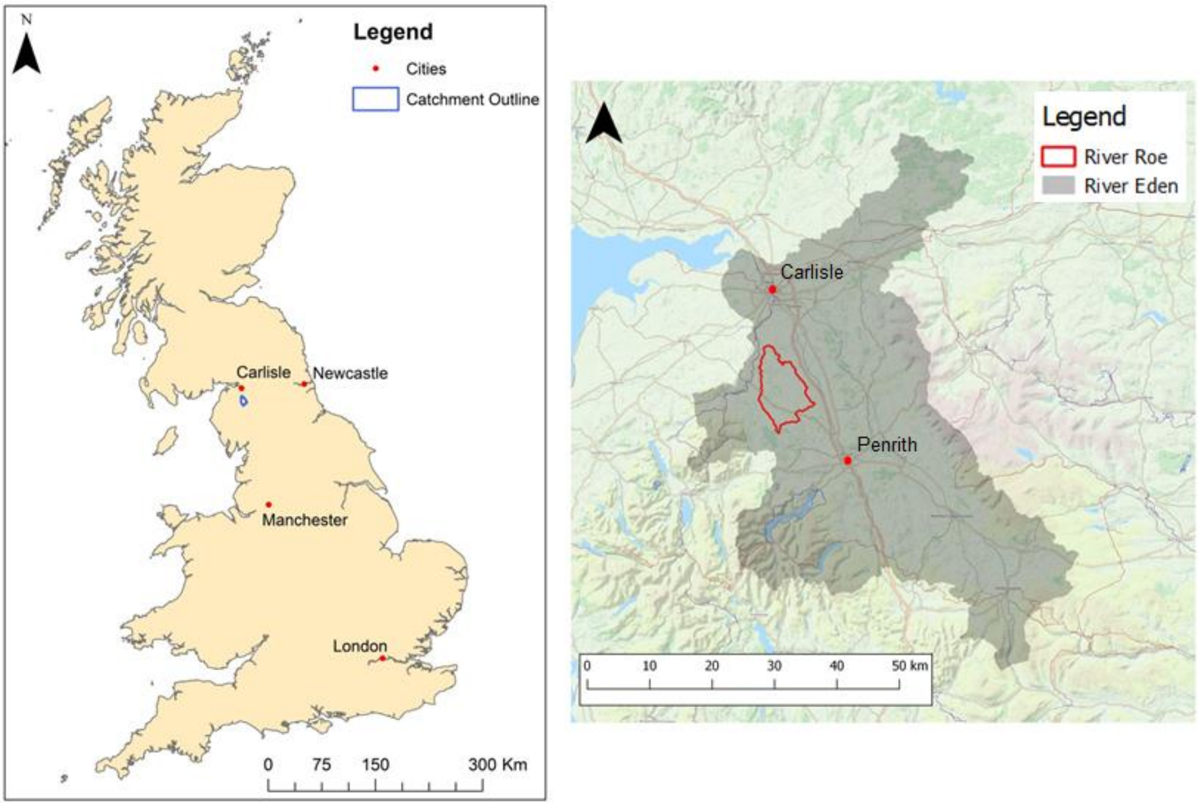

Figure 2.1 The location of the River Roe catchment in relation to the United Kingdom (left) and the River Eden catchment (right). (GB National Outlines [SHAPE geospatial data], Scale 1:250000, Tiles: GB, Updated: 8 June 2005, Ordnance Survey (GB), Using: EDINA Digimap Ordnance Survey Service, <http://digimap.edina.ac.uk>). River Eden base map - Maps © Thunderforest, Data © OpenStreetMap contributors.

2.2 Catchment Characteristics

The hydrological behaviour of the River Roe catchment is significantly influenced the topography (section 2.2.1), channel network (section 2.2.2), local climate (section 2.2.3), geology (section 2.2.4), superficial deposits (section 2.2.5) and soils (section 2.2.6).

2.2.1 Topography

The elevation range within the River Roe catchment is 310m with a maximum elevation of 370m OD in the south-west of the catchment towards the Lake District National Park and a minimum elevation of 59m OD in the north of the catchment where the River Roe meets the River Caldew (Figure 2.2). The highest slope gradient is concentrated around the channel network and the areas of higher elevation with a maximum gradient of 48.5°, (Figure 2.3), based on the analysis of the 5m digital elevation data. The high slope gradient around the channel network results in a limited flood plain and constrains the flow during storm events.

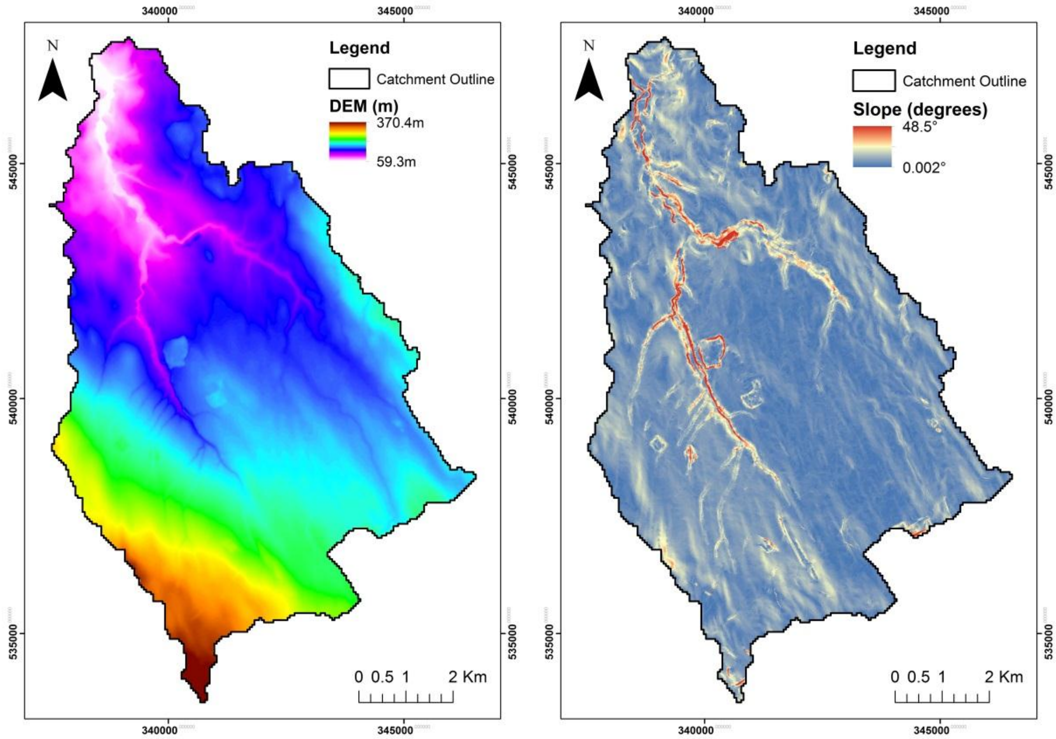

Figure 2.2 (left) is a DEM of the River Roe catchment showing elevation. Figure 2.3 (right) shows the slope in the River Roe catchment. Both derived from 5m resolution data Nextmap data from Intermap.

2.2.2 Channel Network

The channel network it outlined in Figure 2.2 and 2.3 and explored in detail in Figure 2.4. The network is centred on two sub-catchments (Roe Beck and River Ive) which combine near the village of Highbridge to form the River Roe. The Roe Beck sub-catchment is located in the south-west of the catchment and the River Ive sub-catchment located in the south-east; both rivers flow in a northerly direction.

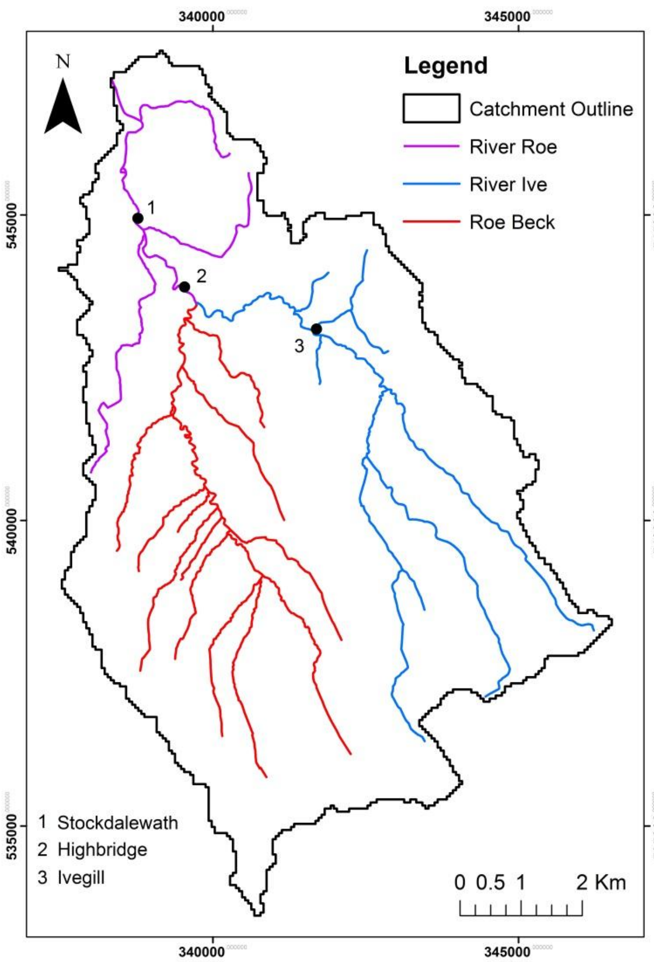

Figure 2.4 The channel network of the River Roe catchment divided to highlight the two sub-catchments (River Ive and Roe Beck) that combine to form the River Roe at Highbridge.

2.2.3 Climate

The annual average rainfall in the River Roe catchment is 984mm between 1961 and 1990 (NERC, 2015). The south-west of the catchment on the edge of the Lake District experiences the greatest amount of precipitation, having an average rainfall of 1493mm annually, whilst the northern part of the catchment receives the least rainfall with an annual average of 810mm (NERC, 2015). The mean monthly rainfall recorded between 1990 and 2014 at Newton Rigg weather station, located 6.5km to the south of the River Roe catchment, is 80.1mm with a maximum of 269.4mm recorded in November 2009 and a minimum of 5.6mm recorded in September 2014 (Met Office, 2015). On average the wettest months occur in the winter (101.6mm month^{-1}) and autumn (92.4mm month^{-1}) with the spring (58.8mm month^{-1}) and summer (67.7mm month^{-1}) months being noticeably drier. The maximum recorded daily rainfall at Newton Rigg weather station throughout the above time period was 60.2mm recorded on the 8th January 2005 (BADC, 2014). The mean daily air temperature recorded between 1990 and 2014 is 8.7°C with a maximum recorded daily air temperature of 31.1°C and a minimum recorded daily air temperature of -17.7°C (BADC, 2014). July is the warmest month with an average maximum temperature of 19.6 °C and December is the coldest month with an average minimum temperature of 0.4°C (Met Office, 2015).

2.2.4 Bedrock Geology

The bedrock is dominated by sedimentary rocks with cyclical sequences of mudstone, sandstone, limestone and siltstone throughout the extent of the River Roe catchment. The Alston Formation, a cyclothermic sequence of limestone, sandstone, mudstone and siltstone, is prevalent in the south-west of the catchment whilst the central area of the catchment features the Pennine Coal Measures Formation (a mudstone, siltstone and sandstone sequence) and the Stainmore Formation (cyclic repetition of sandstone, siltstone and mudstone) (BGS, 2015). After the confluence of Roe Beck and the River Ive the main channel of the River Roe overlies the Penrith Sandstone Formation; coarse grained sandstone layer (BGS, 2015). Deemed a 'Principal Aquifer' by the Environment Agency (2015) the Penrith Sandstone Formation has a high permeability and thus increased water storage potential with the ability to have an effect on the base flow in the River Roe. The other bedrock in the River Roe catchment is categorised as a 'Secondary A Aquifer' which, whilst still permeable and capable of influencing base flow, have a lesser impact than the Penrith Sandstone Formation (Environment Agency, 2015).

2.2.5 Superficial Deposits

Superficial deposits, deposits that were formed during the Quaternary period, in the River Roe catchment are mapped in Figure 2.5. Till, a poorly sorted mixture of clay, silt, sand and gravel, is the central deposit throughout the catchment with river terrace deposits (sand and gravel of fluvial origin) and alluvium (consolidated silty clay) dominating the channel network (Bell, 2002). The south-east of the catchment features areas of glaciofluvial deposits. The deposits in the channel network and the glaciofluvial deposits have been designated 'Secondary A Aquifers' as explained previously whilst the glacial till is categorised as a variable minor or non-aquifer due to differing characteristics throughout the coverage (Environment Agency, 2015).

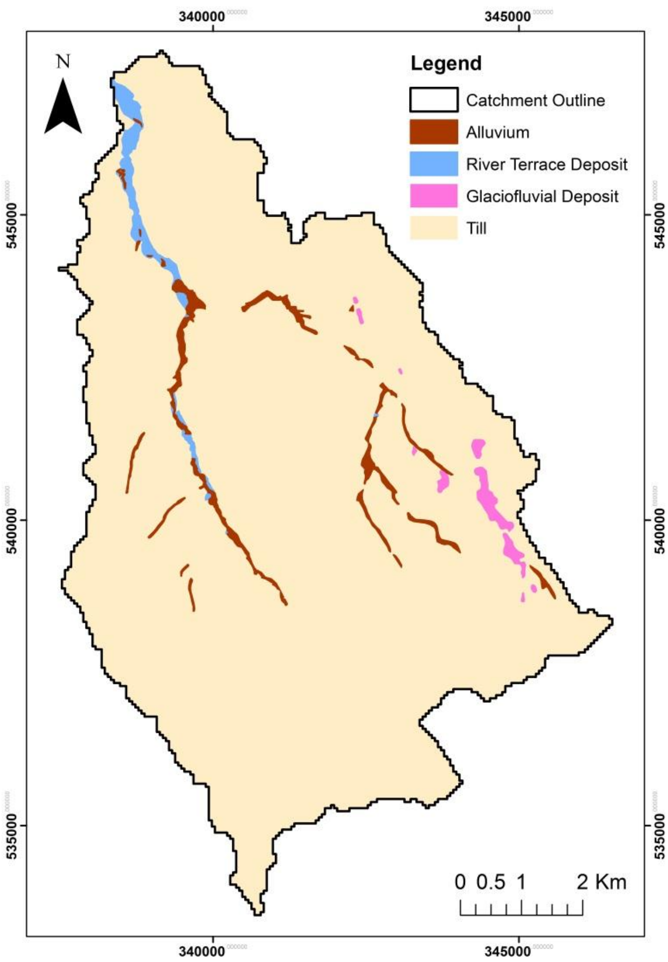

Figure 2.5 Simplified superficial deposits in the River Roe catchment (derived from BGS data on Edina Digimap)

2.2.6 Soils

Figure 2.6 illustrates the spatial composition of soil within the River Roe catchment. The soil in majority of the catchment is of the Clifton soil series; loamy and clayey in texture, developed in loamy till and glaciofluvial deposits and forming rolling terrain incised by the stream network (Cranfield University, 2015). Soils in the Clifton soil series are typically stagnogley soils due to the slowly permeable nature of the till (Cranfield University, 2015). The soil is often seasonally waterlogged and once the subsoil is wet it will remain so for the winter period (Cranfield University, 2015). The soil differs from the aforementioned stagnogley soil to typical brown earth and argillic brown earth soils. In the south of the catchment with soil from the Eardiston soil series is freely draining and loamy in texture and also in the east of the catchment with soil from the Salwick soils series showing less obstruction to drainage that that of the Clifton soil series (Cranfield University, 2015). Table 2.1 highlights the differences evident within the soils of the River Roe catchment using the LandIS Soilscapes from Cranfield University (2015).

	Soilscape 6	Soilscape 8	Soilscape 18
Texture	Loamy	Loamy and some clayey	Loamy and clayey
Drainage	Freely draining	Slightly impeded drainage	Impeded drainage
Fertility	Low	Moderate to high	Moderate
Land Cover	Arable and grassland	Arable and grassland	Grassland, arable and woodland
Drains to	Local groundwater and rivers	Stream network	Stream network

Table 2.1 LandIS Soilscapes descriptions for the three soil classes in the River Roe catchment.

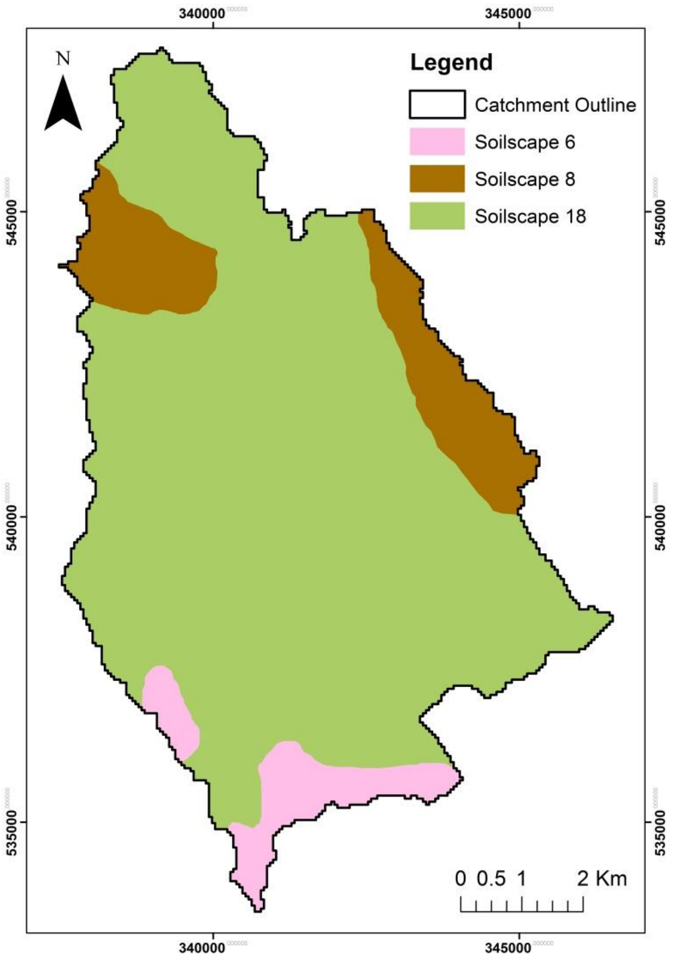

Figure 2.6 Soil map of the River Roe catchment (derived from soil data from LandIS, Cranfield University (2015))

2.3 Land Cover

2.3.1 Present Land Cover

Figure 2.7 shows the spatial distribution of land cover classification for the River Roe catchment ascertained from the Land Cover Map 2007 (LCM2007) data (Centre of Ecology and Hydrology, 2015). Percentage coverage of the LCM2007 classes is shown in Table 2.2. The majority of the catchment is used for agriculture with 82% of the catchment classified as improved grassland for livestock grazing and arable for cereal production. A further 9% is rough semi-natural grassland with low productivity. The woodland in the catchment is concentrated in small block plantations of both deciduous and coniferous woodland and also bordering the stream network; notably in the Roe Beck catchment. There is a sparse population in the catchment and therefore limited urban spatial coverage.

LCM2007 Number	LCM2007 Class	% of Coverage
1	Deciduous Wood	5.13
2	Coniferous Wood	2.85
3	Arable and Horticulture	23.90
4	Improved Grassland	58.08
5	Rough Grassland	7.86
6	Neutral Grassland	0.08
8	Acid Grassland	1.13
10	Heather	0.21
11	Heather Grassland	0.07
14	Bare Ground	0.38
22	Urban	0.14
23	Suburban	0.17

Table 2.2 Percentage land cover for the LCM2007 categories in the River Roe catchment

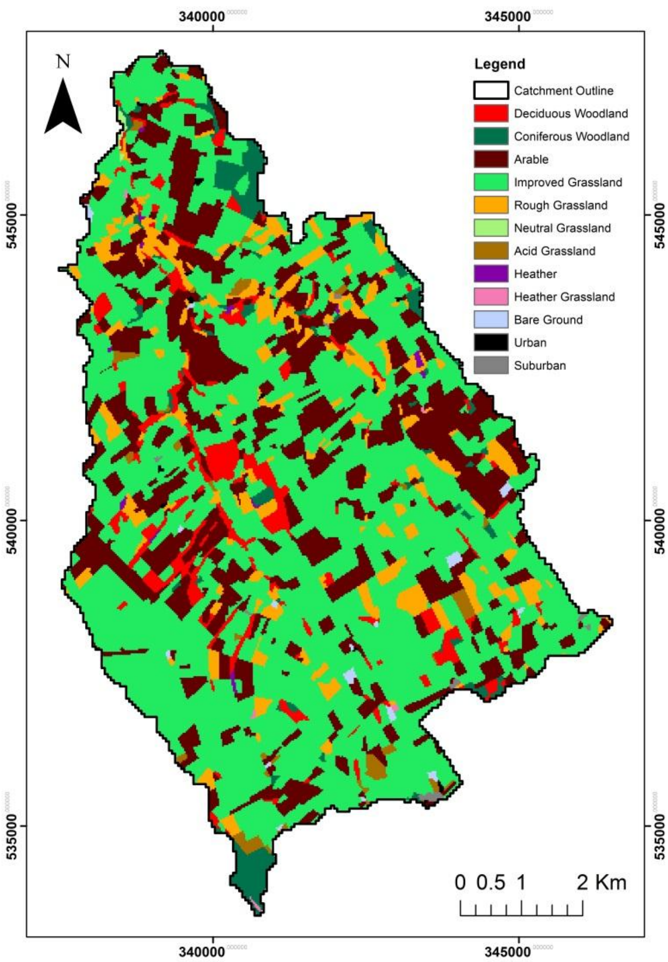

Figure 2.7 Land cover map for the River Roe catchment created using LCM2007 data (Centre for Ecology and Hydrology, 2015)

2.3.2 Historic Land Cover

Throughout the medieval period the River Roe catchment formed part of the Forest of Inglewood which stretched from Carlisle to Penrith and would have been predominantly forested (Cumbria County Council, 2009). Gradual deforestation to increase agricultural output and the shift from common moorland grazing and arable fields to planned enclosures in the 18th and 19th century has left the catchment with its current land coverage of small blocks of woodland plantations and ancient gill woodland surrounded by agricultural land (Cumbria County Council, 2009).

2.4 River Flow

The Environment Agency provided both daily flow data and 15 minute flow data for the River Roe for the time period 2004 to 2014; the gauging station is located in the centre of the village of Stockdalewath and accounts for river flow generated from 63km^2 of the catchment. Figure 2.8 shows a time series of the provided 15 minute river flow data and Figure 2.9 the resulting flow duration curve derived from the data.

The maximum river flow at the gauging station was 98.8m^3/s which was recorded on 8th January 2005. This was calculated using the information provided by the Environment Agency to be a 1 in 12 year return period event; this return period is likely limited the by length of the available data. The UK Meteorological Office suggested that the storm throughout Cumbria had a return period of 1 in 100 years (Environment Agency, 2006). The river flow in the River Eden at the Sheepmount gauging station was estimated to have a return period of between 175 to 200 years and the return period of the flow in the River Caldew in excess of 50 years (Environment Agency, 2006). With the River Roe catchment making up part of the River Caldew catchment it is therefore considered possible that the return period during the 2005 flood event is approximately 1 in 50 years in the River Roe. The second highest maximum river flow was 89.6m^3/s which was recorded on 18th May 2013. The highest daily flow, the average flow over a 24 hour period, was 29.1m^3/s which was gauged on 8th January 2005. The QMED for the River Roe, the median of the recorded annual maximum flows, is 43.5m^3/s (CEH, 2015).

It is evident from the flow data that the River Roe exhibits seasonality with the highest average monthly river flow in the winter months (January, November and December) and the lowest average monthly river flow in the summer months (June, July and August).

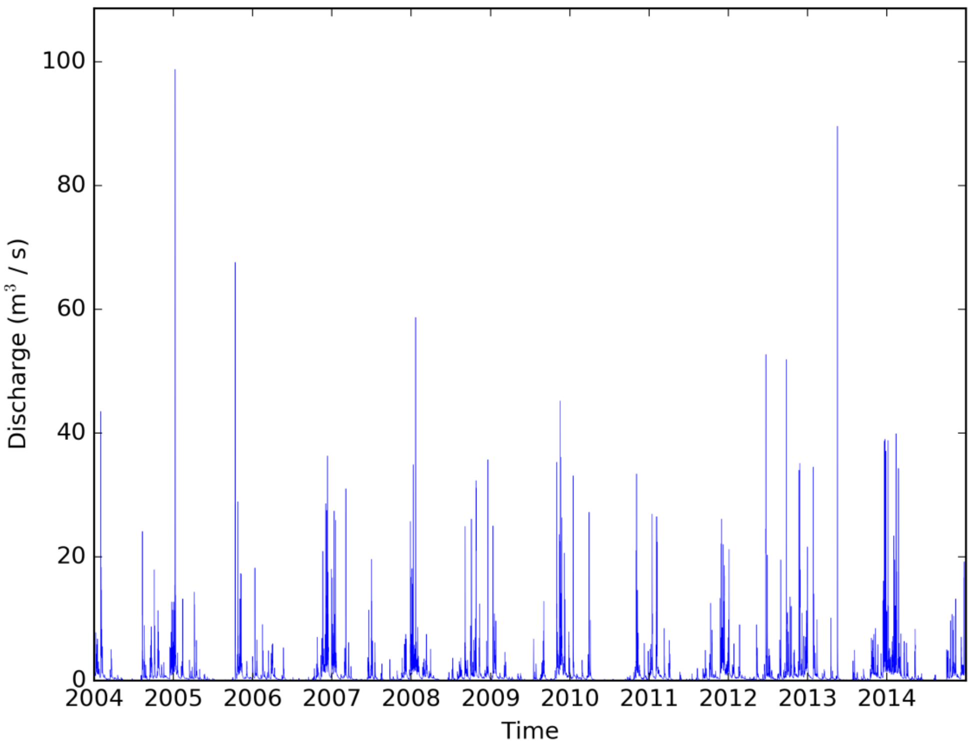

Figure 2.8 A time series of 15 minute flow data for the River Roe at the Stockdalewath gauge for the period 2004 to 2014.

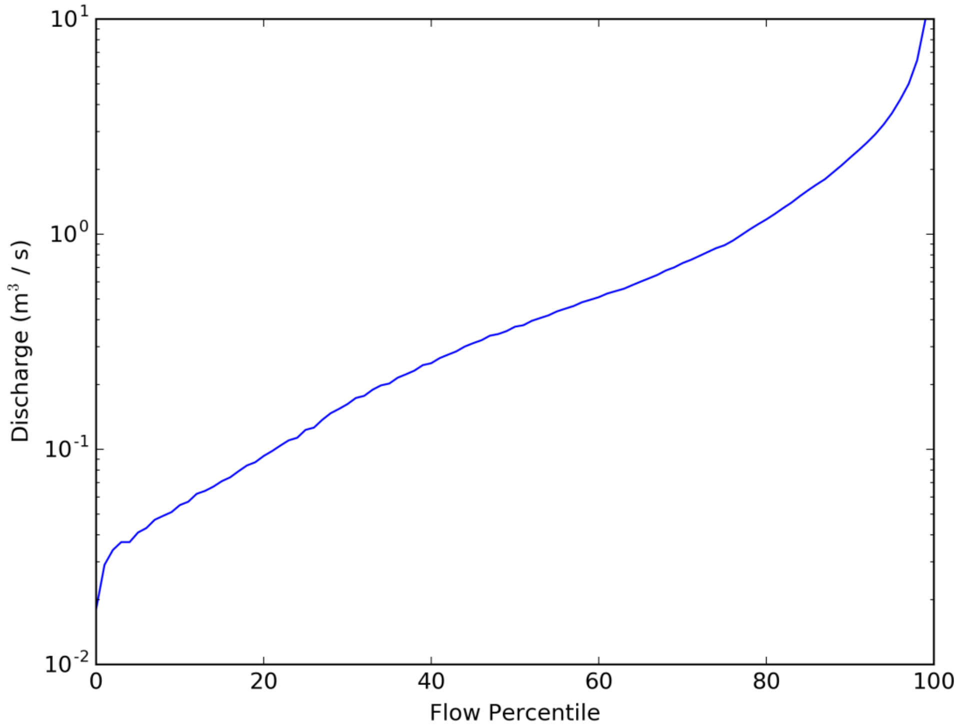

Figure 2.9 The flow duration curve for the River Roe at Stockdalewath derived from the provided Environment Agency flow data.

2.5 Project stakeholders

There are a range of stakeholders involved in this project that include the RCCWMG, the Environment Agency, the Eden Rivers Trust, Cumbria County Council and Durham University. The RCCWMG represented a cross-section of the catchment community, in particular those at risk of future flooding in Stockdalewath, and the relevant government organisations.

2.6 Summary

The River Roe catchment has a small population, centred around the villages of Stockdalewath and Ivegill, and is predominantly agricultural with regards to land cover with 82% of the catchment land either improved grassland or arable in nature. The majority of the soil within the catchment is agriculturally productive and drains to the channel network.

The channel network consists of two tributaries (River Ive and Roe Beck) that form the River Roe at Highbridge. The Roe Beck drains the west of the catchment and is formed from a series of wooded gills and streams that drain the steeper high ground to the west of the catchment. The River Ive is a flatter catchment with gentler terrain that drains the agricultural land to the centre and east of the catchment. There is a high slope gradient around the channel network of the River Roe with a limited floodplain and thus minimal opportunity for flood water to be stored as it flows downstream.

3 Methods

3.1 Introduction

This chapter outlines the methods employed to answer the research aims presented in Section 1.1. Figure 3.1 shows an overview of the research process involved. Section 3.2 details CRUM3 the distributed hydrological model used to assess the impact of the catchment-based land management techniques and interventions in the River Roe catchment. A distributed model was chosen for the ability to represent hydrological processes at a variety of spatial scales (see chapter 1 for more details). Section 3.3 introduces SCIMAP, a risk-based model focused on hydrological connectivity. Section 3.4 describes how both CRUM3 and SCIMAP were used to inform and model management scenarios. Section 3.5 discusses the quantification of the impact of mitigation options of both high and low flows and finally Section 3.6 looks at scenario development through stakeholder participation.

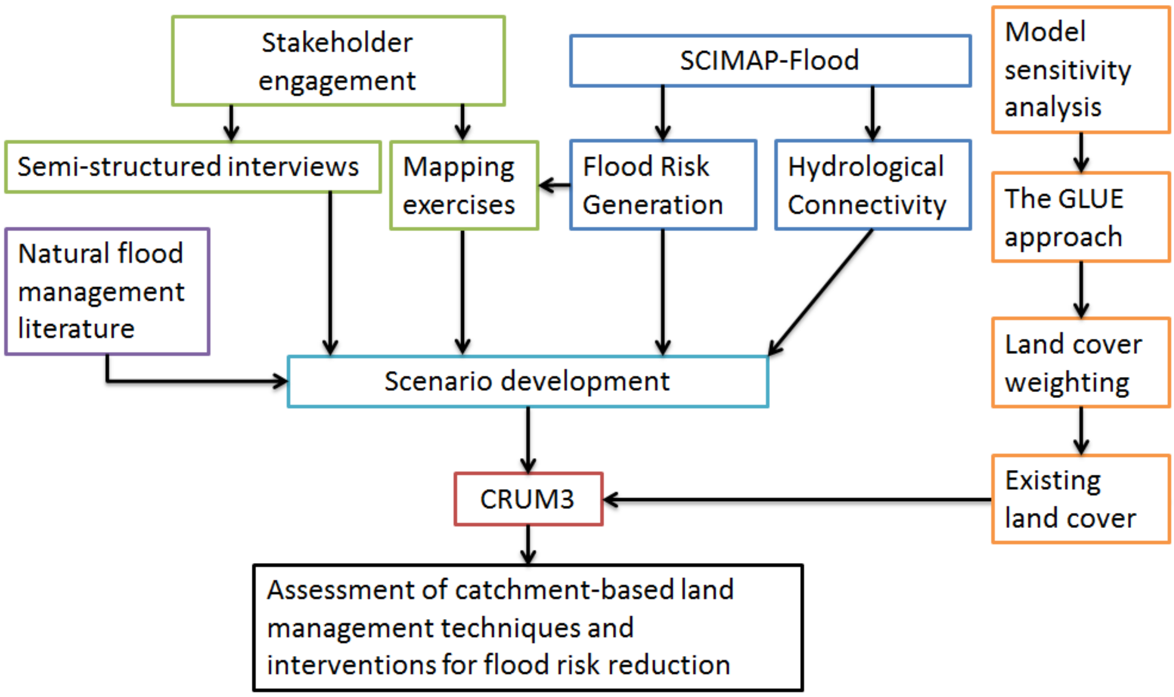

Figure 3.1 Overview of the methods employed in the project

3.2 Hydrological model choice

As explored in section 1.6, there are a range of forms a hydrological model can take; varying in complexity, data requirements and structure. For this investigation a lumped or conceptual model would not be appropriate with the former not representing spatial variation in land cover through the catchment and the latter not assigning physical meaning to parameters. A fully distributed, physically based model is deemed necessary to fulfil the research objectives.

CRUM3 was the hydrological model chosen to investigate land use management techniques with a view to reducing flood risk. CRUM3 has been used for a variety of academic research relevant to the intended outcome of this project; the impact of rural land management on flood risk (Pattison, 2010) and the impact of rural land management on low flows (Smith, 2011). Additionally CRUM3 studies have been successfully implemented in a number of northern UK catchments with projects in Upper Rye catchment, River Eden catchment and Dacre Beck catchment for academic, governmental and industry projects. The River Roe catchment used as a study site is located within the River Eden catchment and hence the suitability of the CRUM3 model for the River Roe has already been established.

As outlined in Lane et al. (2009) the model represents all the vital hydrological processes in a catchment with less data required than similar fully distributed models such as MIKE SHE (DHI, 1999); evapotranspiration, infiltration, throughflow and interception. Furthermore the stochastic nature of the weather generator in CRUM3 allows for natural variability during a storm event to be simulated with rainfall generated in 15 minute time steps. With a high performance computer cluster available at Durham University, the large computational demands of running the model using 50m resolution for the 2005 flood event enabled sensitivity analysis and the GLUE approach (Beven and Binley, 1992) to be utilised.

3.3 Connectivity of Runoff Model (CRUM3)

CRUM3 is a fully distributed, object orientated, process based hydrological model which operates at a landscape scale in surface water dominated catchments (Lane et al., 2009). It was designed to address questions related to the impact on flow extremes from projected climate change and land management techniques whilst using a minimal parameter set derived from accessible national datasets (Lane et al., 2009).

3.3.1 CRUM3 Structure

CRUM3 consists of four key sections; weather, 1D vertical hydrological processes, landscape and river channel network, as taken from Lane et al. (2009). This structure is shown in Figure 3.2 and is explored in detail below.

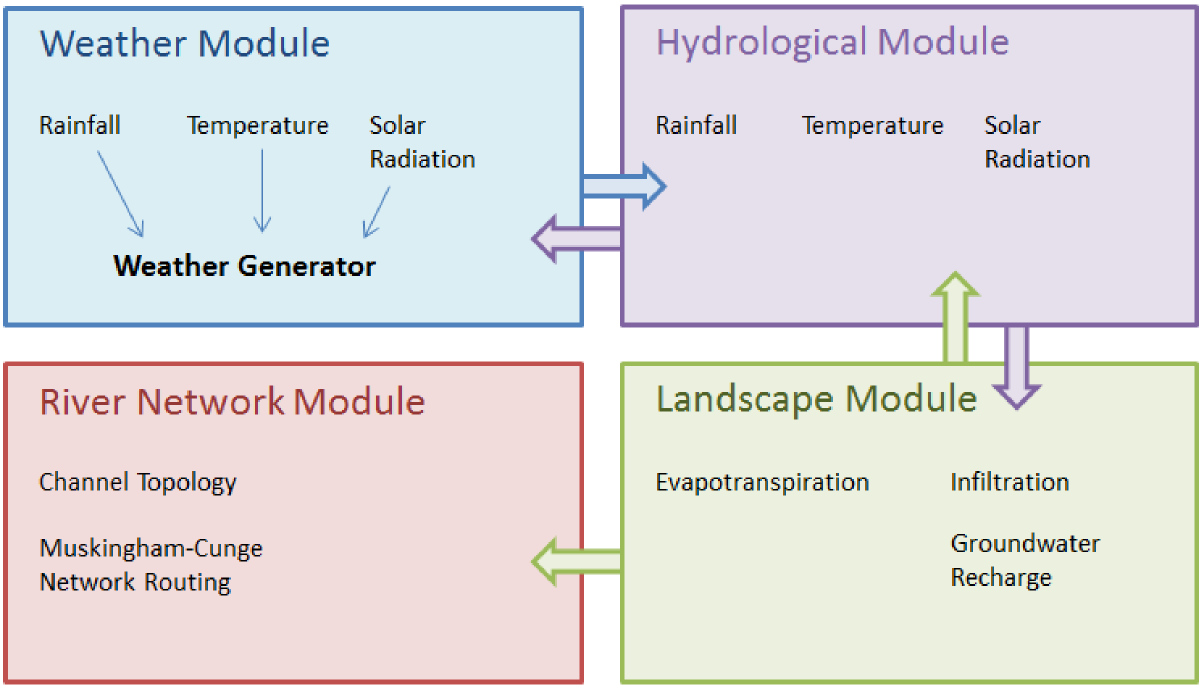

Figure 3.2 Representation of the structure used in CRUM3

3.3.1.1 Weather

Time-dependent and spatially distributed rainfall, temperature and solar radiation data are integrated into the weather module. The temperature and solar radiation information is used to calculate the evapotranspiration rate and timing of vegetation growth whilst the rainfall data forms the dominant hydrological input into the catchment. Hydrological processes related to rapid overland flow generation and flood risk creation occur at per-minute timescale in relation to the generation and transmission of catchment runoff and thus the creation of a per-minute rainfall time series is attained using a stochastic rainfall generator based on the approach used by Mulligan (1996) and explored in detail in Lane et al. (2009). The rainfall generator uses a dataset from a tipping bucket rain gauge to characterise the storm events and daily rainfall totals to produce the long term trends. A Monte Carlo approach was used to create stochastic storm events throughout a day and then generate the per minute rainfall intensities. Solar radiation was calculated throughout the year based on solar geometry using the day of the year and latitude of the catchment. The weather module utilises daily maximum and minimum air temperature from observed records with the corresponding values interpolated into per-second temperature using [EQ1]:

$$T_{a(s)} = \frac{\sin\left(d_s + td + \frac{(12*60*60)}{4*60*60}\right) + 1}{2} * (t_{max} - t_{min}) + t_{min}$$

where $T_{a(s)}$ is the air temperature at the current second, d_s is the current second of the day, td is the time between midday and the maximum daily temperature occurring, t_{max} is the daily maximum temperature, t_{min} is the daily minimum temperature.

3.3.1.2 Point-scale Hydrological Processes

CRUM3 simulates the interception of precipitation by vegetation, the infiltration of water into soil, the recharge of the aquifer from the soil, the storage of water on the soil surface and the generation of throughflow and surface runoff; these processes and relative order are conceptualised in Figure 3.3 (Lane et al., 2009; Smith, 2011).

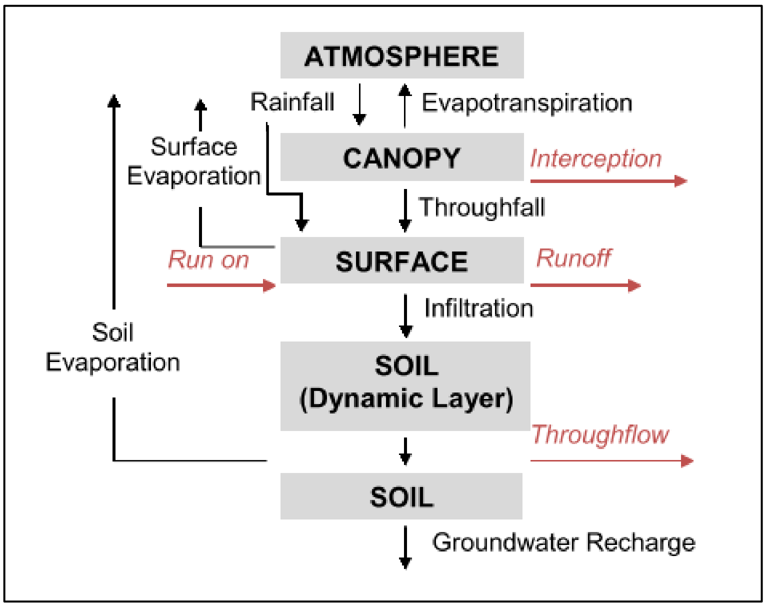

Figure 3.3 The hydrological processes in CRUM3 conceptualised (taken from Smith, 2011)

The canopy is considered a non-leaking store during the process of rainfall interception; the rainfall is divided into throughfall and intercepted water dependent on canopy gap fraction. The intercepted fraction of the precipitation fills the canopy store until it is full and overflows; water is then allowed to leave the canopy store as evaporation. The vegetation type and amount of biomass impacts on the size of the canopy store and percentage of rainfall intercepted.

CRUM3 has the ability to calculate evapotranspiration using both the Priestley-Taylor equations (Priestley and Taylor, 1972) and the Penman-Monteith equation (Penman, 1948; Monteith, 1965). The most accurate estimator of potential evapotranspiration across a range of vegetation types is the Penman-Monteith equation but this approach requires time series information on temperature, solar radiation, wind speed, relative humidity and vegetation information (Dingman, 1994). As not all this information is available for the River Roe catchment the Priestley-Taylor equation was selected as the best compromise between process representation and data requirements. The equation is as follows [EQ3]:

$$PET_{PT} = \frac{a_{PT}\Delta(R_n - G)}{\Delta y}$$

where PET_{PT} is the potential daily evapotranspiration according to the Priestley – Taylor equation, R_n is the net radiation, G is the soil heat flux, Δ is the slope of the saturation vapour pressure temperature relationship, γ is the psychrometric constant; and a_{PT} is the Priestley – Taylor constant location parameter which under normal conditions is 1.26.

The amount of solar radiation at the surface is attained from the amount of energy at the top of the atmosphere, the transmission of the energy through the atmosphere and the reflection of energy by the surface cover. The equations used to determine the amount of energy arriving at the top of the atmosphere are documented in Dingman (1994). Variation in the amount of energy reaching the surface due to scattering depends on atmosphere depth, local weather conditions; cloud cover being the most important. In CRUM3 the reduction in energy through a cloud free atmosphere is determined by [EQ4]:

$$R_{ES} = R_{TA} * 0.5$$

where R_{ES} is the amount of solar radiation reaching the surface and R_{TA} is the amount of solar radiation at the top of the atmosphere. When days are assigned with cloud cover this value is reduced by 50 percent. Days with cloud cover include all days with rain and additionally non-rain days determined using a Monte Carlo model parametrised from observed data. Upon reaching the surface the solar radiation can be either emitted as long wave radiation or directly reflected. Albedo determines the amount of radiation that is reflected off the surface and is given as [EQ5]:

$$r_{sw} = R_{ES} * a$$

where r_{sw} is reflected short wave radiation and a is the surface albedo. The amount of solar energy reflected as long wave radiation is attributed to both temperature and surface emissivity and is determined by [EQ6]:

$$r_{lw} = e_{ms} * (5.6696 * 10^{-8}) * (T_a + 273.15)^4$$

where r_{lw} is reflected long wave radiation, e_{ms} is surface emissivity and T_a is the air temperature (°C). Once the reflected solar radiation has been subtracted the remainder impacts on the evapotranspiration process.

To establish the amount of actual evapotranspiration from the potential amount predicted in the Priestley-Taylor equation involves evaporating water on the vegetation, soil surface, in the soil and transpiration. Evaporation of standing water from the soil surface and vegetation canopy occurs at the potential rate. The potential transpiration is related to the leaf area index of the vegetation and is represented as (Scott, 2000) [EQ7]:

$$t_p = PET_{PT} * (-0.21 + 0.7^{LAI})$$

where t_p is potential transpiration, PET_{PT} is potential daily evapotranspiration according to the Priestley – Taylor equation and *LAI* is the leaf area index. The amount of actual transpiration can be related to the availability of water in the dynamic layer and main soil store in addition to the vegetation rooting depth.

The water retention characteristics of the soil affect the amount of evaporation achieved from water travelling through the soil matrix. It is a linear relationship that accounts for increased tension at low soil moisture levels [EQ8]:

$$e_\theta = PET_{PT}\theta$$

where e_θ is the soil moisture evaporation rate, PET_{PT} is potential daily evapotranspiration according to the Priestley – Taylor equation and θ is the soil moisture (m^3 water/m^3 pore space).

Surface gradient and roughness determine the depth of the surface depression and detention stores. The depression store is the water within the troughs of the surface due to roughness and the detention store is water detained above the depression store and is able to move as overland flow. From Kirkby et al. (2002) the surface depression store depth is calculated as [EQ9]:

$$\frac{dp}{a} = 0.11exp(-\frac{0.02B}{a})$$

where *dp* is the surface depression storage capacity (mm), *a* is the surface roughness and *B* is the slope gradient. A value for *a* can be related to the random roughness coefficient (*RR*) (Allmaras et al., 1966) by [EQ10]:

RR = 0.657*a*

Overland flow in CRUM3 is generated in three ways; infiltration excess overland flow, saturated overland flow and return overland flow. With saturated soil conditions rainfall is no longer able to infiltrate into the soil and is converted to saturated overland flow. Return overland flow occurs when the storage capacity of a cell is exceeded by throughflow entering the cell from upslope and thus water overflows out of the top of the cell. Infiltration excess overland flow takes place when the rate of rainfall is above that of the soils infiltration capacity; rainfall will infiltrate at a maximum rate and excess water will develop into overland flow. Infiltration is defined through a simplification of the Green and Ampt (1911) equation developed by Kirkby (1985) [EQ11]:

$$i = a + \frac{b}{\theta}$$

where *i* is the infiltration rate, a and *b* are coefficients and θ is soil moisture.

Soil depth exerts a significant control on the hydrological processes whilst working at a point-scale; Huggett and Cheesman (2002) state there is a clear relationship between soil depth and geomorphological form. To represent the differences the soil properties related to surface topography, CRUM3 classifies the landscape into ridges, slopes, channels and plain areas and assigns consistent soil properties within these regions.

The rate of groundwater recharge in CRUM3 is derived from the minimum of the hydraulic conductivity at the soil profile base and the hydraulic conductivity of the underlying bedrock.

3.3.1.3 Landscape scale processes

With CRUM3 utilising spatial information within a raster grid structure each cell generates and receives water laterally through overland flow and throughflow. Overland flow can occur under laminar, transitional and turbulent conditions and is represented using the Darcy-Weisbach equation (Abrahams et al., 1992; Baird, 1997) [EQ12]:

$$v = \sqrt{\frac{8gRs}{ff}}$$

where *v* is the velocity of overland flow ($m^3\ s^{-1}$), *g* is the gravity constant, *s* is the slope (degrees) and *ff* is the friction factor. Through flow volume is determined by Darcy's Law in the saturated zone [EQ13]:

$$tf_v = wt * y * K_d * \frac{dh}{dx}$$

where tf_v is the throughflow volume per second ($m^3\ s^{-1}$), wt is the height of the water table above the bedrock (m), y is the width of the routing facet (m), K_d is the soil hydraulic conductivity at the water table depth ($m\ s^{-1}$), h is the hydraulic head (m) and x is the horizontal distance between model cells (m). The soil hydraulic conductivity is represented through [EQ14]:

$$K_d = K_{sat} \exp\left(\frac{-d}{dc}\right)$$

where K_d is the soil conductivity at the water table depth (m s^{-1}), K_{sat} is the soil saturated conductivity, *d* is the depth of the water table and dc is the decay factor for change in hydraulic conductivity with depth.

Routing of overland flow within CRUM3 is calculated using the FD8 algorithm (Quinn et al., 1991). Unlike a single flow routing method, such as D8, FD8 allows for water to flow from one cell to multiple others aiding the representation of flow dispersion and concentration. The amount of flow allocated to each cell is achieved on a slope-weighted basis (Quinn et al., 1991; Freeman, 1991) [EQ15]:

$$F_i = \frac{\beta_i^v}{\sum_{i=l}^{8} \beta_i^v}$$

where β_i is the slope from the central node to a neighbour (*i*) and *v* is a positive constant. The *v* constant is a flow concentration factor and an increased value of *v* results in an increased concentration of flow; Holmgren (1994) suggests between 4 and 6 for distributed modelling.

At each model iteration, the flow directions and hydraulic gradients are updated for both the surface and sub-surface flows. This updating allows for the surface depression to fill and overflow and hence allows for greater realism in the simulations.

3.3.1.4 River channel network

The Muskingham-Cunge model (Ponce and Lugo, 2001) is used to represent the movement of water in the channel network. Each river reach is associated with a landscape cell and receives water from both overland flow and throughflow in addition to receiving water from other upstream river reaches. The discharge from a river channel cell is determined by [EQ16]:

$$Q = (C_0 * U) + (C_1 * U_1) + (C_2 * Q_1)$$

where Q is existing discharge (m^3 s^{-1}), Q_1 is the discharge from the previous time step, U is the inflow from the upstream reach, U_1 is the inflow from the upstream reach from the existing time step and C_0, C_1 and C_2 are routing coefficients. The routing coefficients are explored in detail in Lane et al. (2009).

The topology of the network is determined by DEM analysis for flow directions, slope gradients and the upslope contributing area. The landscape is deemed to be a river channel location when the upslope contributing area exceeds 0.8 km^2; this is the value used in Lane et al. (2009).

3.3.2 Data Requirements

Weather and spatial data are required for CRUM3 to function; additionally discharge measurements from a suitable river flow gauge can be used for model validation. The process by which this data is used within CRUM3 is explained in the previous section (3.3.1). The necessary weather data for the model is temperature, both minimum and maximum, and daily precipitation. This data was attained from the Met Office MIDAS dataset held at the British Atmospheric Data Centre (BADC). For this research the rainfall data was from the Skelton weather station (BADC identification number – 13056, NY 435360) which is located at the southern end of the River Roe catchment. The temperature data was taken from the Newton Rigg weather station (BADC identification number – 1073, NY 492308), which is located 8km to the south of the catchment, was chosen as the Skelton weather station did not have temperature measurements available and temperature is consistent over a large spatial area. The daily river discharge data used is from National River Flow Archive (NRFA) from the Centre of Ecology and Hydrology (CEH) using the gauging station at Stockdalewath (NRFA identification number – 76019, NY OS grid reference: 387450). The site of the gauging station accounts for flow from 63km^2 of the 69km^2 River Roe catchment and is located the centre of the 2005 and 2013 flood events. For the investigation of the impact of catchment-based land management techniques and interventions for flood risk management it was decided that data from the 2005 flood event would be selected for modelling; the 2005 flood event witnessed the highest discharge at the Stockdalewath gauging station and caused extensive damage in the catchment. Weather and discharge data was attained for the period of July 1st 2004 until January 31st 2005 to allow for a more accurate representation of the conditions leading up to the January 8th 2005 flood event.

3.3.3 Sensitivity Analysis

Sensitivity analysis evaluates the impact of changes of model parameters and inputs on the desired model output (Sorooshian and Gupta, 1995). As a distributed model CRUM3 has a large number of model parameters and sensitivity analysis can be undertaken to help determine which processes have the greatest impact on the hydrological regime in the catchment (Pechlivanidis et al., 2011). Preliminary assessment eases model calibration through highlighting parameters that greatly impact on the intended output and those that have a negligible effect (Crosetto et al., 2000). As in Pattison (2010) each parameter is assigned an upper and lower bound determined through literature and is then evenly sampled within this range whilst every other parameter is kept at a base value; the impact of each parameter is then assessed by quantifying change in the hydrograph. An insensitive parameter will exhibit little effect in the model output whilst a sensitive parameter will show a large variation. Sensitivity analysis in this investigation was determined using the flow duration curve so to understand the model's response to a range of flows.

3.3.3.1 Parameter Range

Citing previous research done on sensitivity analysis for CRUM3 (Pattison, 2010; Baugh, 2010; Smith, 2011) each parameter was altered methodically from the existing base values to encompass a range determined through a lower and upper limit. These parameter values are evident in Table 3.1 below and each parameter was tested independently with the other soil, land cover and channel parameters kept at base value.

Parameter	*Lower Limit*	*Base Value*	*Upper Limit*
Soil Parameters			
Saturated Conductivity (K_{SAT}) (m/s)	1×10^{-8}	2×10^{-4}	1×10^{-3}
K_{decay} with depth	-9	-3	-1
Soil Porosity (ϕ) (decimal %)	0.01	0.451	0.7
Soil Depth Channels (m)	0.1	1.0	2.0
Soil Depth Slopes (m)	0.05	0.16	1.2
Soil Depth Ridges (m)	0.2	0.5	1.5
Soil Depth Plains (m)	0.2	0.5	1.5
Dynamic Layer Depth (m)	1×10^{-5}	0.05	0.5
Dynamic Layer K_{SAT} (m/s)	2×10^{-5}	9×10^{-3}	2×10^{-2}
Dynamic Layer *b* parameter	0	4.05	16
Bedrock Conductivity (m/s)	1×10^{-11}	2.5×10^{-10}	1×10^{-7}
Green and Ampt *a* parameter (mm/hr)	0	10	100
Green and Ampt *b* parameter (mm/hr)	0	5	100
Land Cover Parameters			
Canopy Gap Fraction (decimal %)	0	0.2	1.0
Maximum Vegetation Height (m)	0	1.0	15
Canopy Interception Depth (m)	0	0.002	0.01
Albedo (decimal %)	0.05	0.1897	0.5
Darcy-Weisbach Friction Factor	0	75	500
Per cent of cell with overland flow (decimal %)	0.1	0.3	1.0
Vegetation Growth Rate (g/sec/m^2)	0	0.02	1
Vegetation Growth Temperature Threshold (°C)	0	5	10
Channel Routing Parameters			
Hydraulic Geometry *k*	0.1	1.0	2.0
Hydraulic Geometry *m*	0.1	0.32	0.5
Discharge per unit width	0.1	5.0	10.0

Table 3.1 Parameter values for sensitivity analysis (Clapp and Hornberger, 1978; Dingman, 1994; Reaney et al., 2005; Baugh, 2010; Pattison, 2010).

Each parameter was tested with five evenly spaced values above both the lower and upper limit with a central existing base value. For example the Hydraulic Geometry k parameter would have sensitivity analysis values of 0.1, 0.28, 0.46, 0.64, 0.82, 1.0, 1.2, 1.4, 1.6, 1.8 and 2.0.

The sensitivity of the parameters in Table 3.1 was assessed using the flow duration curve (FDC) for the modelled 2005 flood event where the percentage of time a specified flow is equalled or exceeded can be quantified. Despite this study concentrating on predominantly on high flow events both low and high flows were considered during sensitivity analysis with the average change in Q01, Q05, Q95 and Q99 between the altered parameters and the model run with the existing base value parameter figures being accounted for; Q01 refers to the discharge being equalled or exceeded one percent of the time and Q99 refers to the discharge equalled or exceeded ninety-nine percent of the time. This quantification was achieved using [EQ17] and [EQ18]:

$$Cd_i = \frac{A_v - B_v}{B_v} * 100$$

where Cd_i is the change in discharge for *i* equals Q01, Q05, Q95 and Q99, A_v is the altered discharge value and B_v is the base value discharge value.

$$F_{cd} = \frac{\sum_{i=1}^{n} Cd_i}{n}$$

where F_{cd} is the final change in discharge and Cd_i is the change in discharge for *i* equals Q01, Q05, Q95 and Q99.

3.3.4 Generalised Likelihood Uncertainty Estimation (GLUE)

Equifinality is the concept that more than one combination of parameters can result in the same outcome and thus have the same model performance strength (Pechlivanidis et al., 2011). Therefore we cannot think of there being one preferred model parameter set but a group of equally suitable parameter sets (Beven, 2006; Pechlivanidis et al., 2011). With a move towards more robust uncertainty frameworks in hydrological modelling, the GLUE approach, (Beven and Binley, 1992), uses Bayesian estimators to evaluate the likelihood that different combinations of parameter sets are suitable predictors of hydrological behaviour (Wainwright and Mulligan, 2004). GLUE utilises a Monte Carlo simulation and a likelihood measure, such as Nash-Sutcliffe efficiency, to determine the degree of acceptability in a model (Pechlivanidis et al., 2011). The approach aims to avoid over-conditioning to obtain a single parameter set and allows subsequent model runs to use an ensemble of parameter sets to give the best predictions (Pechlivanidis et al., 2011). The main limitation of using the GLUE approach is the dependency of a cut-off threshold value to define acceptable (behavioural) and unacceptable (non-behavioural) simulations (Pechlivanidis et al., 2011). Additionally with the number of model runs required to complete the GLUE analysis there is a high associated computational cost. The result of the GLUE analysis enables the capturing of the model predictive uncertainty within the final result and thus gives a clearer indication into predicted changes in flood flows.

3.3.4.1 Parameter Choices

The GLUE approach uses groups of parameters to develop multiple sets of model output; consequently through equifinality different parameter sets could perform equally well at predicting the observed flow (Stedinger et al., 2008; Pechlivanidis et al., 2011). The parameter sets selected for GLUE analysis are the most responsive parameters from the aforementioned sensitivity analysis. There are usually less than six model parameters involved in GLUE analysis (Smith, 2011) however with the excellent computational resources available, this investigation is able to take a greater number of parameters forward into the GLUE analysis.

The 24 CRUM3 parameters analysed for sensitivity using the process outlined in Section 4.2 are ranked in Figure 4.1 using soil, channel and land cover categories. Whilst this study concentrated on flood risk reduction and thus high flow events there is also the need, as defined in the project aims, to consider low flows and ensure that the model represents both effectively. Therefore, the ten most sensitive parameters averaged from discharge change for Q01, Q05, Q95 and Q99 are utilised; these range from an average 5.05 percentage change to 69.59 percentage change. These parameters are saturated conductivity, bedrock conductivity, K decay with depth, dynamic layer depth, soil porosity, plain soil depth, slope soil depth, albedo, channel soil depth and the Darcy-Weisbach friction factor.

3.3.4.2 Latin Hypercube Sampling

Whilst the Monte Carlo simulation method is widely used for uncertainty problems in hydrological modelling it depends on random number generation to sample parameter space and requires a great number of model runs to represent all probable results (Beven, 2009; Pechlivanidis et al., 2011, Milledge et al., 2012). Smith (2011) ascertained that 10,000,000,000 model runs would be required to adequately cover the parameter space using the Monte Carlo method and thus a more effective method is necessary. This can be achieved using less informed approaches in which segments of probability distributions are split or stratified (Jackson, 2007). The Latin Hypercube sampling technique is such an alternative solution which divides the range of values for each parameter into ordered segments of equal probability and combines individual samples to produce parameter ensembles (Helton and Davis, 2003).

The Latin Hypercube sampling approach was developed using the *lhsdesign* function in MATLAB. Through X = *lhsdesign*(*n,p*) a *n*-by-*p* matrix (X) is returned; this contains a Latin Hypercube sample of *n* values on each of *p* variables (MathWorks, 2015). For each column of X, the *n* values are randomly distributed with one from each interval (0,1/n), (1/n,2/n), ..., (1-1/n,1), and they are randomly permuted (MathWorks, 2015). The *lhsdesign* function generates Latin Hypercube samples to find the most suitable according to the criteria of '*maximin*' which maximises the minimum distance between points and '*correlation*' which reduces correlation. For this investigation the criterion was set to '*maximin*', there were 100 iterations used and a sample size for of 5000 was determined appropriate for 10 variables. Additionally the upper and lower parameter values used for the sensitivity analysis were run three times, the mean parameter values run three time and the base values run five times. The use of the Latin Hypercube sampling design ensures that each model simulation adds the greatest amount of information on the behaviour of the model since it removes redundancy of multiple model simulations with very similar parameterisation. This experimental design culminated in 5014 model runs which were completed in a week on a High Performace Computing cluster at Durham University.

3.3.4.3 GLUE model performance

On completion of the 5014 GLUE model runs a performance measure was required to assess each run's performance at predicting the observed values from the selected time period. There are numerous performance indicators in literature but a combination of Nash-Sutcliffe Efficiency (NSE), Log Nash-Sutcliffe Efficiency (LNSE) and absolute flood peak ratio (AFPR) was determined to be the most suitable performance measure for investigating land use management techniques and interventions with a view to reducing flood risk (Reaney, 2015 per. comm.).

NSE, developed by Nash and Sutcliffe (1970), is the most common technique for model performance analysis and determines the relative magnitude of the residual variance compared to the measured data variance. The NSE gives a greater weight to high flow values and thus the LNSE offers an alternative to the NSE by using logarithmic values of the observed and predicted to reduce the problems associated with squared differences and the subsequent sensitivity to extreme values (Krause et al., 2005; Legates and McCabe, 1999). LNSE increases the influence of low flow values through flattening the values of high flow events; the combination of both methods assesses both high and low flows. With the study looking at reducing a peak flow event the maximum flow of the model run was considered with the desire to test the effectiveness of flood risk reduction techniques and interventions. The involvement of the AFPR as a performance measure ensures that the predicted maximum discharge is comparable to that of the observed. The Nash-Sutcliffe Efficiency (E) is calculated as [EQ19]:

$$E = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

where O_i is the observed discharge at time (*i*), P_i is the observed discharge at time (*i*) and $\bar{O}$ is the average observed discharge. The Nash-Sutcliffe Efficiency with logarithmic values is calculated as [EQ20]:

$$E = 1 - \frac{\sqrt{\sum_{i=1}^{n}(O_i - P_i)^2}}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}}$$

where O_i is the observed discharge at time (*i*), P_i is the observed discharge at time (*i*) and $\bar{O}$ is the average observed discharge. The range of *E* lies, for both NSE and the subsequent LNSE, between 1.0 (perfect fit) and -∞ with an efficiency of lower than zero indicating that the mean value of the observed discharge would be a better predictor of the model (Krause et al., 2005). And the AFPR was calculated as [EQ21]:

$$AFPR = 1 - (abs\left(1 - \frac{P_{max}}{O_{max}}\right))$$

where O_{max} is the maximum observed discharge, P_{max} is the maximum predicted discharge and abs ensures it is an absolute value. The AFPR works so that a value of 1.0 would witness the maximum predicted discharge as equal to the maximum observed discharge.

This performance assessment was achieved through rescaling the NSE, LNSE and AFPR values for the model runs on a 0 to 1 scale and multiplying the performance measures [EQ22]:

$$Model\ Performance\ Indicator = NSE * LNSE * FPR$$

The performance measures were completed using mean daily discharge for the simulated time period; the available 15 minute time step data for the observed data had missing information due to a fault in the gauging station during the notable high flow event. The daily discharge was calculated from 0900 until 0900 as with the observed data from the Environment Agency. Additionally, the assessment of the model performance at the daily timescale helps eliminate the impact of the stochastic weather generator.

3.4 Spatial Land Cover Representation in CRUM3

Variation in the area and category of land cover has the potential to have a significant impact on the hydrological regime of a catchment; as is evident in the literature reviewed in Section 1.3. Above it has been demonstrated that CRUM3 can be applied to both high and low flows and represents the 2005 storm event satisfactorily. However with the selected top 30 GLUE model runs having utilised a homogenous catchment land cover and soil properties it is necessary to apply weighted land cover and corresponding soil categories to the model to better represent the River Roe catchment. Catchment-based land management techniques and interventions, as outlined in Section 1.5, often employ the alteration of vegetation and soil properties and thus the ability to differentiate between land cover categories is essential before flood risk reduction testing can begin.

The original twelve land cover categories from the LCM2007 data (Figure 2.9 and Table 2.2) were reclassified to six categories. The Deciduous Woodland, Coniferous Woodland and Arable categories remained the same. Improved Grassland incorporated the Bare Ground category, the Urban and Suburban categories were combined and a 'Natural Grassland' was created from the Rough Grassland, Neutral Grassland, Acid Grassland, Heather and Heather Grassland categories. The percentage land cover for the reclassified categories is in Table 3.2 and spatially evident in Figure 3.4. Following the reclassification soil and land cover parameter values were acquired from relevant literature for the six land cover categories; they will be used to describe the relationship between categories for each parameter. The attained values for the land cover parameters used in CRUM3 are illustrated in Table 3.3 and the soil parameters in Table 3.4 below. As in Smith (2011) figures established from literature given as zero were represented as 1^{E-9} as the division of zero gives infinite solution.

LCM2007 Number	Simplified LCM2007 Class	% of Coverage
1	Deciduous Wood	5.13
2	Coniferous Wood	2.84
3	Arable	23.91
4	Improved Grassland	58.54
5	Natural Grassland	9.27
22	Urban	0.32

Table 3.2 Catchment percentage cover under the reclassified LCM2007 data.

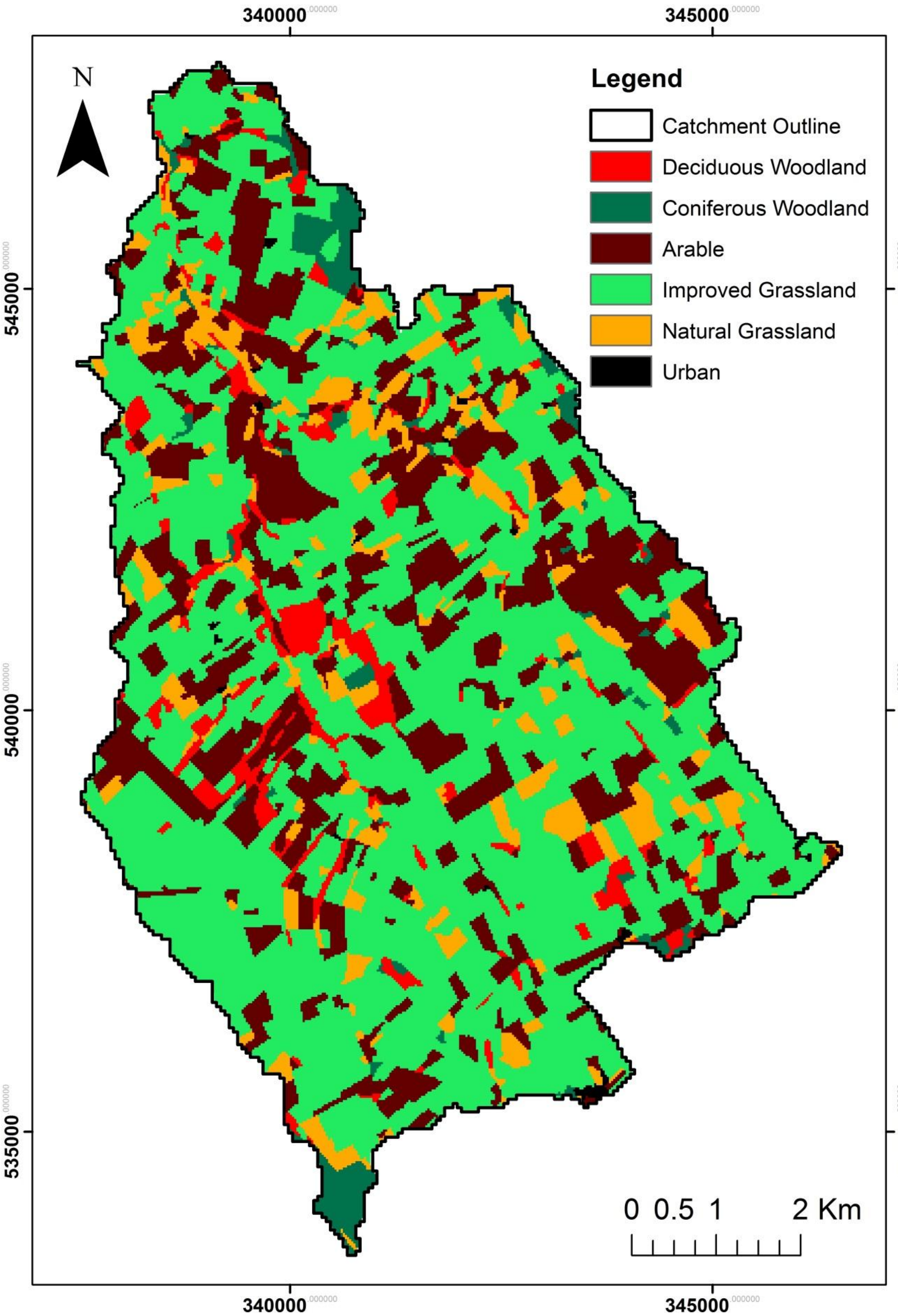

Figure 3.4 River Roe catchment land cover under the reclassified LCM2007 data

	Interception Depth (m)	Canopy Gap Fraction (decimal %)	Albedo (decimal %)	Max Vegetation Height (m)	Darcy-Weisbach FF	Vegetation Growth ($g/sec/m^2$)	% Cell Overland Flow (decimal %)	Growth Temp (˚C)
Deciduous Woodland	0.00287	0.2	0.18	18.2	1.5	4.37E-05	0.3	7.2
Coniferous Woodland	0.00296	0.2	0.15	24.3	1.5	1.65E-05	0.3	5
Arable	0.00289	0.4	0.25	1.44	2.17	0.0006	0.3	4
Improved Grassland	0.0015	0.05	0.2	1.35	3	0.000055	0.3	4
Natural Grassland	0.0015	0.05	0.25	1.35	3	0.000075	0.3	4
Urban	1.00E-09	1.0	0.16	0.0001	0.5	1.00E-09	0.3	5
Source	(Breuer and Frede, 2003)	Reaney et al., 2005).	Barry and Chambers, 1966; Dingman, 1994; Breuer and Frede, 2003)	Næsset, 1997; Breuer et al., 2003; Herbst et al., 2007)	(Gilley et al., 1992; Gilley and Kottowitz, 1994; Abrahams et al., 1995; Musleh and Cruise, 2006; Parsons and Abrahams, 2009)	(Sims and Singh, 1978; Cropper and Golz, 1993; Birch et al., 2000; Ganapathi, 2006)	(Reaney et al., 2005)	(Kozlowski et al., 1962; Birch et al., 2000; Kilpeläinen et al., 2005)

Table 3.3 Literature values for land cover parameter values

	Channel Soil Depth (m)	Slope Soil Depth (m)	Ridge Soil Depth (m)	Plain Soil Depth (m)	Dynamic Layer K_{SAT} (m/s)	K_{SAT} (m/s)
Deciduous Woodland	1.5	0.24	0.75	0.75	0.000126	0.00132
Coniferous Woodland	1.3	0.2	0.625	0.625	0.000126	0.00023
Arable	0.986	0.158	0.493	0.493	7.78E-05	0.00028
Improved Grassland	1	0.16	0.5	0.5	7.78E-05	0.00051
Natural Grassland	1	0.16	0.5	0.5	7.78E-05	0.00051
Urban	1	0.16	0.5	0.5	2.45E-07	0.00005
Source	(Pattison, 2010)	(Pattison, 2010)	(Pattison, 2010; Schulze et al., 1996)	(Pattison, 2010; Schulze et al., 1996)	(Pirastru et al., 2013; Pattison, 2010)	(Gonzalez-Sosa et al., 2010)

Table 3.4 Literature values for soil parameter values

	Dynamic Layer Depth (m)	Dynamic Layer *b* Parameter	Green Ampt *a* Parameter (mm/hr)	Green Ampt *b* Parameter (mm/hr)	Porosity (decimal %)	K Decay with depth	Bedrock Conductivity (m/s)
Deciduous Woodland	1.9	4.05	10	5	0.74	-9.8	2.5E-10
Coniferous Woodland	2.1	4.05	10	5	0.73	-9.8	2.5E-10
Arable	1.43	4.05	10	5	0.58	-4.37	2.5E-10
Improved Grassland	0.93	4.05	10	5	0.69	-4.9	2.5E-10
Natural Grassland	0.93	4.05	10	5	0.69	-4.37	2.5E-10
Urban	0.05	4.05	10	5	0.41	-7.8	2.5E-10
Source	(Breuer et al., 2003)	(Smith, 2011)	(Smith, 2011)	(Smith, 2011)	(Bodhinayake and Si, 2004; Meyles et al., 2006; Gonzalez-Sosa et al., 2010)	(Youngs, 1976; Beven, 1984; Elsenbeer et al., 1999)	(Smith, 2011)

Table 3.4 cont'd. Literature values for soil parameter values

The parameter values in the literature between the different land covers and the disparity is essential in representing the variation between the land cover parameters from the GLUE results. The existing area of each land cover in the River Roe catchment was taken into account during the proportional rescaling of the parameters for the top 30 ranked GLUE runs. With 58.4 percent coverage the Improved Grassland was the dominant land cover category for use in the process which was developed with Reaney (2015 per. comm.) and is detailed as [EQ23]:

$$A = \frac{LITvalue}{ImpG\ LITvalue}$$

$$B = A * GLUEvalue$$

$$C = A * B$$

$$D = LCOVarea * C$$

$$E = (DecW\ D + ConW\ D + Ara\ D + ImpG\ D + NatG\ D + Urb\ D)$$

$$F = C * (\frac{GLUEvalue}{E})$$

$$G = \frac{F}{GLUEvalue}$$

$$Scaled\ Parameter\ Value = GLUEvalue * G$$

where $LITvalue$ is the parameter value as derived from literature, $GLUEvalue$ is the corresponding parameter value from one of the top 30 GLUE model runs, $LCOVarea$ is the area of the relevant land cover and $DecW, ConW, Ara, ImpG, NatG\ and\ Urb\ D$ represent the six catchment land covers. This proportional rescaling creates individual parameter values for each land cover in the top 30 ranked GLUE runs whilst maintaining the original representation of the catchment discharge. Using an example of the rescaling and the variation between GLUE runs for Dynamic Layer Depth the original value under homogenous land cover for GLUE1 was 0.3186 and is rescaled to 0.5335 for Deciduous Woodland, 0.4015 for Arable and 0.0140 for Urban. For GLUE3 the original value under homogenous land cover was 0.2389 and is rescaled to 0.4001 for Deciduous Woodland, 0.3012 for Arable and 0.0105 for Urban. The rescaled parameters can now be for the creation of soil and land cover parameter sets for each of the six land covers. The spatial distribution of the aforementioned parameter sets is represented through a land cover map (such as Figure 3.4) and can, as will be explored in the subsequent chapter, be manipulated to simulate land cover change.

3.5 SCIMAP-Flood (Sensitive Catchment Integrated Modelling and Analysis Platform)

SCIMAP is a modelling framework that returns risk-based analysis on a catchment scale using limited input data (Reaney et al., 2011). SCIMAP identifies critical source areas using a topographic network index by means of a relative numerical scale (0 to 1) within the catchment (Lane et al., 2004; Heathwaite et al., 2005; Lane et al., 2009). Using the same principles of hydrological connectivity associated with diffuse pollution modelling, SCIMAP-Flood has been developed to gain an understanding into the runoff regime at a catchment scale; the processes undertaken are evident in Figure 3.5 below.

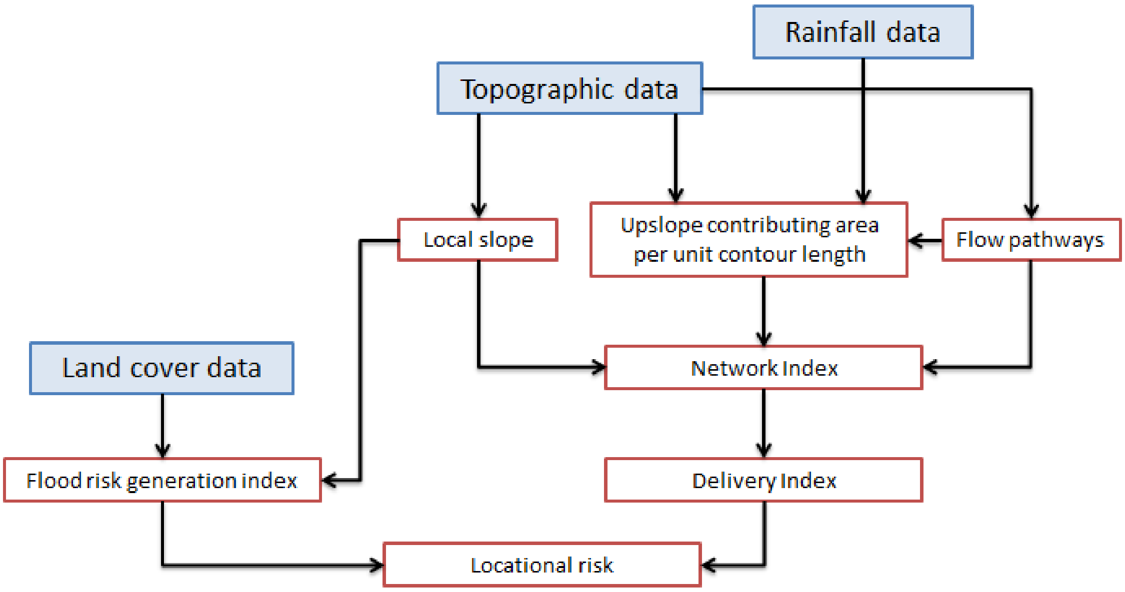

Figure 3.5 Diagram illustrating the processes used in SCIMAP-Flood to calculate relative flood risk at a catchment scale

Critical Source Areas (CSA) (Heathwaite et al., 2005) occur when there is both a source of floodwater waters and a pathway or connection to the river of lake. Therefore, by calculating the spatial pattern of both sources and hydrological connectivity on a scale of zero to one and then multiplying the maps, it is possible to identify and map the CSA. As shown in Figure 3.5, the sources of flood waters are determined by the local land cover, with the risk weightings in Table 3.5, and the local slope gradient; runoff generation increasing with slope gradient (Bracken and Croke, 2007). The hydrological connectivity is determined using the Network Index (Lane et al., 2004) which determines the catchment wetness required for each location in the landscape to be capable of generating runoff and for every location along the flow path to the river or lake to be capable of transmitting the water. The Network Index shows the ease with which each location can contribute water for flood flows.

The SCIMAP-Flood risk management framework requires three main data sources: topographic data, land cover data and rainfall data. For this investigation in the River Roe catchment the topographic data is from the NEXTMap 5m resolution DEM (see Figure 2.2), the land cover data is from the Centre for Ecology and Hydrology Land Cover Map 2007 data (see Figure 2.9) and the rainfall is from the Met Office 5km 1961-1990 baseline average rainfall data (see Figure 2.5). Each land cover class is assigned a runoff value between 0 and 1 with the greater the value the more rainfall is mobilised as runoff. The runoff indices were taken from Rich (2014) and are evident in Table 3.5. The output from SCIMAP-Flood used in the investigation is hydrological connectivity data and flood risk generation data. How this data was used to investigate catchment-based land management techniques and interventions is explored in the subsequent section.

LCM2007 Class Number	LCM2007 Class	Runoff Value
1	Broadleaved Woodland	0.3
2	Coniferous Woodland	0.3
3	Arable and Horticulture	0.7
4	Improved Grassland	0.6
5	Rough Grassland	0.5
6	Neutral Grassland	0.5
8	Acid Grassland	0.5
10	Heather	0.5
11	Heather Grassland	0.5
14	Inland Rock	0.8
22	Urban	0.8
23	Suburban	0.7

Table 3.5 Runoff indices used in SCIMAP-Flood for the River Roe catchment taken from Rich (2014).

3.6 Scenario development through stakeholder consultation

To help develop flood risk reduction scenarios for model testing stakeholder engagement was used for both semi-structured interviews and a mapping exercise were utilised. Between October 2014 and July 2015 semi-structured interviews and meetings were undertaken with key stakeholders in the River Roe catchment; the aim of the interviews was to ascertain suitable natural flood management solutions for the catchment. Semi-structured interviews offer a freedom to let the participant shape the interaction and the way in which the interview aims are answered (Dunn, 2005). The interviewees were members/staff from the Roe Catchment Community Water Management Group, the Eden Rivers Trust, Durham University and the Environment Agency. The range of stakeholders engaged with ensured that a range of organisations involved in reducing flood risk in the River Roe catchment were considered.

A meeting was organised in July 2015 with stakeholders to develop and identify potential catchment-based land management techniques and interventions that could be implemented in the River Roe catchment. Participatory approaches were used to gather feedback from stakeholders about different interventions that could be used through group discussion and mapping exercises. A booklet was created and distributed that established the positive and negative aspects of a variety of natural flood management interventions to ensure that every participant could contribute in an informed manner; the information was taken from Environment Agency (2011) and (2012) outlining impact on flow, cost of implementation and maintenance and other environmental considerations. The meeting was attended by representatives from the Roe Catchment Community Water Management Group, the Eden Rivers Trust, the Environment Agency, Durham University and Cumbria County Council. The mapping exercise involved an open discussion in which any member of the group could detail potential scenarios on the map. Maps from the SCIMAP-Flood Flood Risk Generation output were brought along to aid the locating of interventions through highlighting areas of high runoff and thus flood risk generation; Figure 3.6 is an example are of the A3 SCIMAP-Flood maps brought to the meeting. These maps covered the entire catchment and allowed representatives from regional and national organisations an insight into runoff generation in the catchment in addition to helping validate local knowledge. Potential natural flood management solutions were then drawn and annotated on A3 OS 1:25,000 maps. The results of this meeting and the themes identified throughout the semi structured interviews are presented in Chapter 4 where they are expanded into flood risk reduction scenarios and modelled using CRUM3.

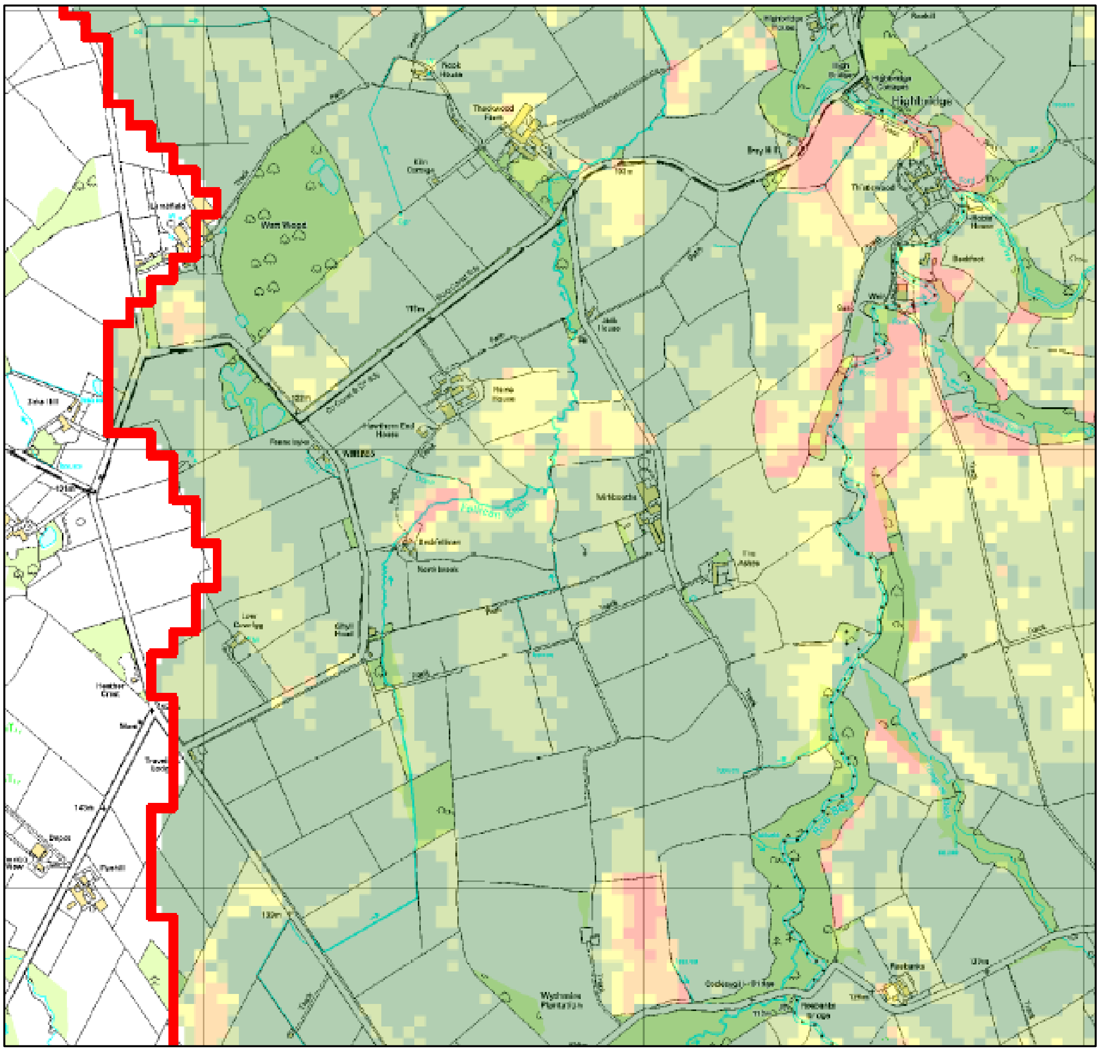

Figure 3.6 An example extract from the A3 SCIMAP-Flood flood risk generation maps used in the mapping exercise to help stakeholders determine various locations for certain natural flood management interventions.

3.7 Modelling catchment-based land management techniques and interventions using CRUM3

Following sensitivity and GLUE analysis CRUM3 was then used to simulate a variety of catchment-based land management techniques and interventions. These different management scenarios incorporate land use change such as afforestation and buffer strips (3.7.1), soil compaction management through aeration (3.7.2) and natural flood management interventions such as woody debris dams (3.7.3).

3.7.1 Land cover change

CRUM3 was used to simulate land cover change through the alteration of spatial land cover information; the data was taken from the CEH Land Cover Map 2007 (LCM2007) (CEH, 2011) and entered into the model as an ASCII file. As in Smith (2011) the land cover data was simplified, from the original 12 categories in the River Roe catchment to six: deciduous woodland, coniferous woodland, arable, improved grassland, natural grassland and urban. The six individual land cover categories were assigned weighted land cover and soil parameters and based on the results from the GLUE analysis; parameters altered include saturated conductivity, soil porosity, albedo, dynamic layer depth and vegetation height.

The initial land cover change scenario was complete coverage of the River Roe catchment with each of the six land cover categories. Though unrealistic with regards to implementation, these scenarios gave an indication of the greatest predicted impact that potential land use change could have on both the maximum and minimum flows within the catchment. The hydrological connectivity and flood risk generation values from SCIMAP-Flood were also used to inform land cover change scenarios with afforestation implemented using targeted values from the relative scale. Additionally conventional land management techniques, as explored in the literature review, such as riparian buffer zones, field buffer zones and targeted afforestation were turned into scenarios. The impact of land cover change is explored in Chapter 4.

3.7.2 Soil compaction management

Previous research has recognised the impact on flood peaks and low flows that soil compaction levels (Boardman, 2003; O'Connell et al., 2007; Posthumus et al., 2008; Pattison, 2010; Smith, 2010). With the improved grassland and arable land cover categories dominating the land use in the River Roe catchment there was a need to simulate the effects of reducing the compaction levels through soil aeration and livestock grazing management. This was achieved in CRUM3 by altering the soil parameters of both the arable and improved grassland land cover categories to represent the hydrological behaviour of compacted and non-compacted soils. Compaction was modelled using scenarios changing both categories at a catchment scale, in addition to using SCIMAP-Flood output to locate high risk fields to aerate as with land cover change. The values of soil porosity, soil depth and saturated conductivity were changed to simulate changing infiltration rates and the impact this has on discharge. The rate of change in compaction levels was created using Low, Medium and High compactions levels from Smith (2011) and Pattison (2010) and relationship between the compaction levels is shown in Table 3.6. The results for the soil compaction management scenarios are presented in Chapter 4.

	Light Compaction	Medium Compaction	Heavy Compaction
Porosity	0.55	0.515 *(x 0.936)*	0.492 *(x 0.8945)*
Saturated Conductivity	6.95E-4	6.95E-5 *(÷ 10)*	6.95E-6 *(÷ 100)*
Dynamic Layer K_{SAT}	6.95E-5	6.95E-6 *(÷ 10)*	6.95E-7 *(÷ 100)*
Dynamic Layer Depth	0.01	0.00978 *(x 0.97774)*	0.00971 *(x 0.97138)*
Channel Soil Depth	1.0	0.978 *(x 0.97774)*	0.971 *(x 0.97138)*
Slope Soil Depth	0.16	0.156 *(x 0.97774)*	0.155 *(x 0.97138)*
Ridge Soil Depth	0.5	0.489 *(x 0.97774)*	0.485 *(x 0.97138)*
Plain Soil Depth	0.5	0.489 *(x 0.97774)*	0.485 *(x 0.97138)*

Table 3.6 Parameter values used to derive soil compaction scenarios. The italics indicate the relationship to the light compaction levels (Pattison, 2010).

3.7.3 Natural flood management interventions

Modelling natural flood management interventions was also undertaken using scenarios simulated in CRUM3. Woody debris dams and ditch barriers were simulated through the restriction of discharge allowed through a specific river reach cell. This was implemented with number dams placed across tributaries throughout the River Roe catchment with effectiveness assessed through discharge reduction at sub-catchment and catchment scale. To develop scenarios for quantifying the impact of LWD dams, the Strahler stream order was applied to the channel network. With previous research into LWD dams stating that they are best applied to smaller channels it was determined that channels with a Strahler number of 1, 2 and 3 were to have LWD dams applied. Environment Agency (2011) research ascertains that LWD dams should be concentrated where the channel is surrounded by woodland with to high floodplain roughness and the ability to source timber locally; only channel reaches which flow through woodland were selected. Scenario creation using both of these natural flood management interventions and the corresponding impact on flood risk reduction is reported in Chapter 4.

3.7.4 Quantifying the effects of catchment-based land management techniques and interventions using CRUM3 on high and low flows

Despite the aim of this research investigating flood risk reduction and concentrating predominantly on high flow events the impact on the low flow regime in the catchment has to be considered. Statistical analysis on the scenarios modelled using CRUM3 was employed on both high and low discharges, based on the flow duration curve, with changes to both flow regimes being considered before an effective flood risk reduction solution could be enforced. Comparison of the aforementioned flood risk reduction scenarios for high flows will be quantified through the reduction in maximum flow from the simulated 2005 flood event. For a comparison of the effect of the flood risk reduction scenarios on the low flow regime in the catchment the change in Q99, the flow exceeded 99% of the time, will be analysed.

3.8 Summary

This chapter has outlined the methods employed throughout the project. It has detailed the processes involved within the CRUM3 hydrological model and the steps required to create a suitable representation of the hydrological regime of the River Roe catchment; this involved sensitivity analysis, the GLUE approach and then land cover weighting and the results are presented in the following chapter. The creation of flood risk reduction scenarios was explored with results from stakeholder engagement, natural flood management literature and SCIMAP-Flood output utilised to develop a variety of scenarios. The establishment of individual scenarios and the corresponding results is also presented in the following chapter.

4 The potential impact of land use management interventions for flood risk reduction at the catchment scale

4.1 Introduction

This chapter presents the research results; it introduces the establishment of the CRUM3 hydrological model, the feedback from the stakeholder engagement and the processes and corresponding results of the developed flood risk reduction scenarios. Section 4.2 outlines the results of the model setup with the sensitivity analysis, GLUE and land cover weighting results. This chapter will culminate with the hydrological regime for the existing land cover in the River Roe catchment established and from which the effectiveness of the flood risk reduction scenarios can be assessed. Section 4.3 has the results and themes taken from the stakeholder engagement exercises that were used to help inform potential natural flood management techniques and interventions for scenario development. Section 4.4 shows the process involved in the development of each scenario, from blanket catchment land cover change to soil compaction and large woody debris dams, and the results from each developed scenario assessing the impact on maximum discharge. The results from the SCIMAP-Flood analysis and process in which they were utilised are shown in section 4.4.2 (hydrological connectivity) and 4.4.3 (flood risk generation). Section 4.5 investigates the impact of the flood risk reduction scenarios on the catchment low flow regime. Section 4.6 assesses which of the tested flood risk reduction scenarios is most suitable for the River Roe catchment.

4.2 Model establishment

Section 4.2.1 and 4.2.2 contain the results of the sensitivity analysis and the GLUE approach respectively with the methodology outlined in the previous chapter. Section 4.2.3 illustrates how different land cover categories were weighted and applied to the GLUE results to represent the existing catchment land cover. The results of section 4.2.3 were then compared to the flood risk scenarios to determine the impact of the modelled natural flood management interventions and techniques.

4.2.1 Sensitivity analysis results

Figure 4.1 shows the range in sensitivity of the parameters with some being unresponsive and others very sensitive to value alteration. CRUM3 parameters such as Maximum Vegetation Height (average % change in discharge of 0.03) and Green and Ampt *α* parameter (0.08%) were unresponsive to change and thus change from the existing base value has a minimal influence on the hydrological regime in the study catchment. Other parameters were far more responsive with Saturated

Conductivity (69.59%), Bedrock Conductivity (45.68%), K decay with depth (22.98%) and Dynamic Layer Depth (18.01%) exhibiting a significant hydrological response to parameter change across both high and low flows. Examples of the two least responsive parameters and the four most responsive parameters are given in Appendix A and B respectively.

The sensitivity of parameters associated with soil characteristics highlighted the importance of analysis for both the high and low flow regimes. Soil porosity, saturated conductivity and the four soil depth parameters exhibited a variation in catchment discharge when altered from the ascribed base value, with deeper and more porous soil promoting a lower discharge during storm events. From the parameters used in vegetation and land cover representation the surface albedo and Darcy-Weisbach friction factor impacted on flow. Finally the conductivity of the catchment bedrock changed the discharge with porous bedrock increasing the high flow values. With the parameters assessed on an individual basis the GLUE approach was applied to develop an understanding of parameter interaction with a view to accurately representing the hydrological regime in the River Roe catchment.

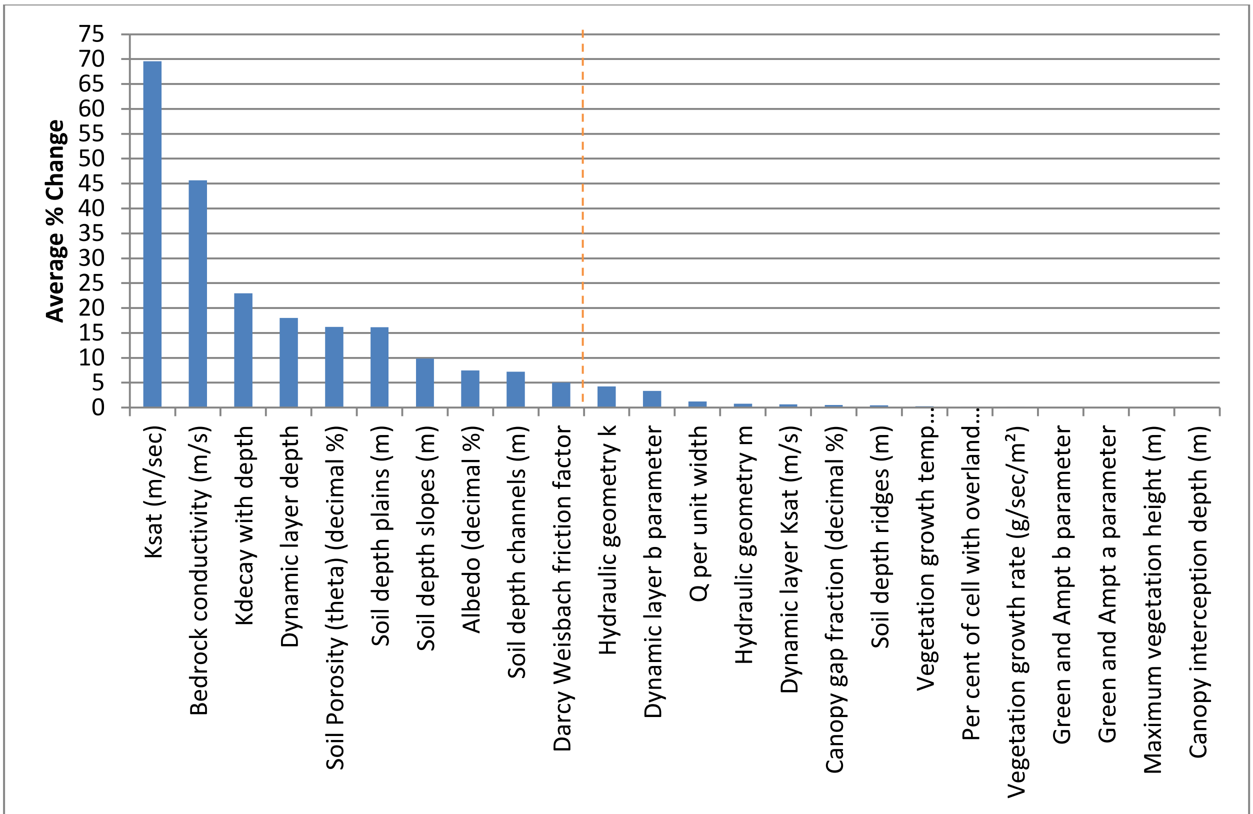

Figure 4.1 Average percentage change in discharge for Q01, Q05, Q95 and Q99 for each CRUM3 model parameter. Parameters to the left of the orange line were used in the GLUE experiment.

4.2.2 GLUE Results

Each of the 5014 model runs were subject to performance testing through NSE and LNSE; as stated in Krause et al. (2005) those with an efficiency of lower than zero indicate that the mean value of the observed discharge would be a better predictor of the model and thus were removed prior to scaling the model runs. Moriasi et al. (2007) ascertain that NSE values of between 0 and 1 can be viewed as acceptable performance. Originally there was a NSE range of -2.56 to 0.69 and a LNSE range of -110.45 to 0.84. The removal process left 1239 model runs remaining that had both an NSE and LNSE of above zero and an updated NSE range of 0.0009 to 0.686 and a LNSE range of 0.00117 to 0.843. The Absolute Flood Peak Ratio (AFPR) range for the 5014 runs was 0 to 0.999 and changed to 0.033 to 0.999 upon the NSE and LNSE informed model reduction. The top 30 ranked NSE*LNSE*AFPR model runs were chosen for further development and the model performance measure values are evident in Appendix C with the corresponding parameter ensembles in Appendix D (following Reaney, 2015 per. comm.). The results of the GLUE experiment are evident in the dotty plots (Appendix E) which illustrate the model performance across each of the ten tested sensitive parameters in relation to the performance measure.

The overall performance of the top 30 GLUE model runs is shown in Figure 4.2. This data was compared to observed data for the simulated 215 day time period involving the 2005 flood event. Using average daily flow data the model runs under predict the lesser high flow events and over predict low flows, including the 2005 storm event. The use of a stochastic rainfall generator and daily rainfall data in CRUM3 alters the specific timings of a rainfall event which may not reflect reality, disturbing hydrograph lag times, and redistributing clusters of rainfall events. These changes lead to a reduced flood peak. With this investigation concentrating principally on the 2005 flood event it was essential that this was acceptably simulated and the maximum discharge was similar to the observed 98.8m^3sec^{-1}. It should be noted that there is uncertainty in the estimation of the 2005 flood peak at Stockdaelwath with the Environment Agency rating curve for the gauge valid to 53.9m^3sec^{-1} and the extrapolation rating curve valid to 124.2m^3sec^{-1}. Additionally this could be the result of the Environment Agency flow gauge at Stockdalewath failing to register flow recordings during the extreme flow event as evident in the 15 minute discharge data in Figure 4.3 where a period is missing. Figure 4.3 highlights the flow limits in which the top 30 model runs predict the 2005 flood event and but also how the stochastic rainfall generator alters rainfall timing with the peak arriving later in the simulations.

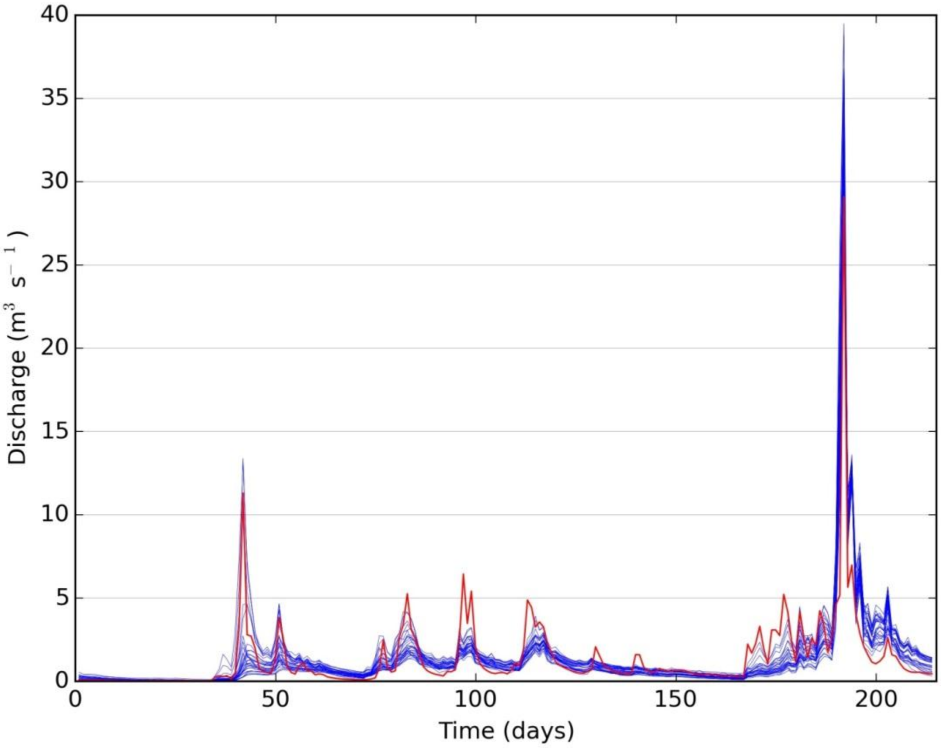

Figure 4.2 Average daily flow for the simulated time period up to and including the 2005 flood event (day 191). Red line is the daily observed data from the Environment Agency. Blue lines are the top 30 GLUE model runs.

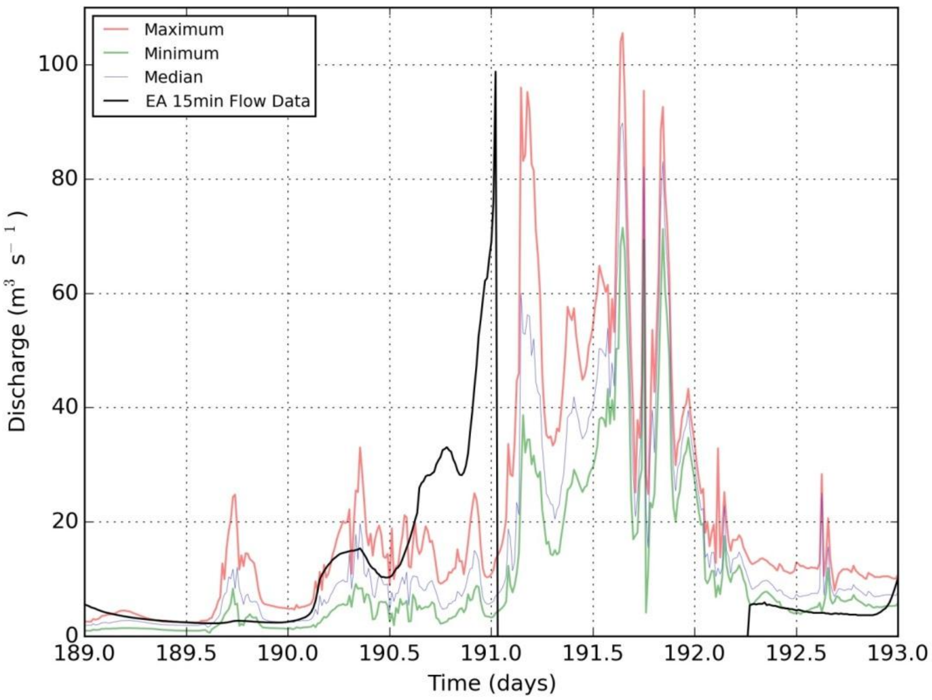

Figure 4.3 15 minute flow data showing the maximum, minimum and median flow from the top 30 GLUE runs. The Environment Agency gauge did not register flow from 0130 on 08/01/05 (day 191) until 0630 on 09/01/05 (day 192) hence the usage of daily data in model performance assessment

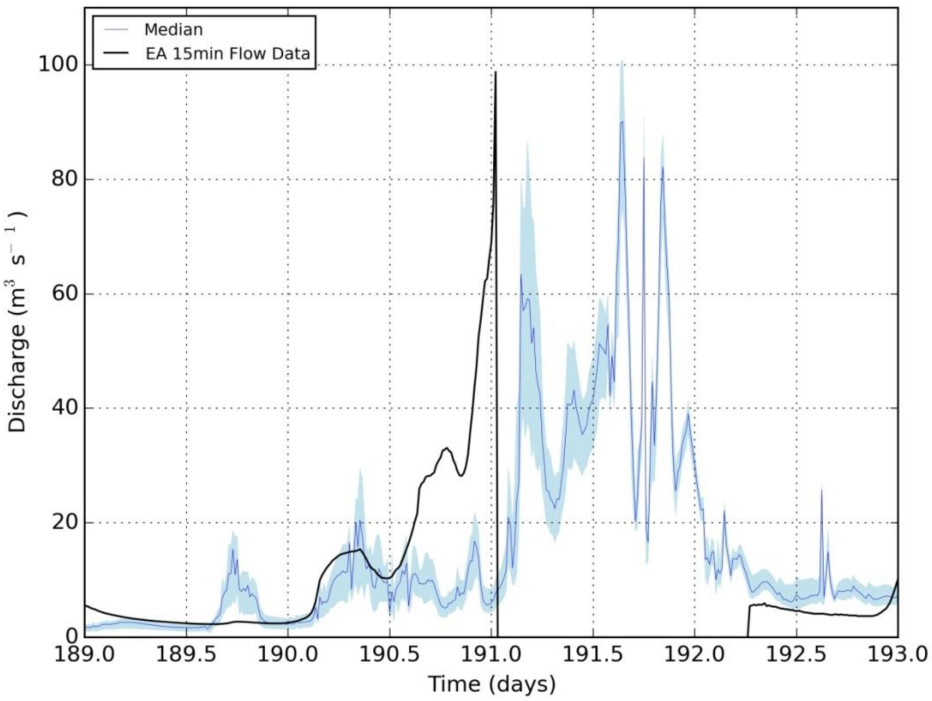

Figure 4.4 15 minute flow data showing the maximum, minimum and median flow from the top 30 GLUE runs using the weighted land cover parameter sets and existing catchment land coverage. The shaded light blue area represents the range between the 10th and 90th percentiles.

4.2.3 Spatial representation of land cover results

The hydrograph for the 2005 flood event for the weighted parameter sets and existing land coverage is presented above in Figure 4.4. As with Figure 4.3 the stochastic nature of the weather generator plays a pivotal role in the shape of the graph, however the flood peak discharge is similar to the observed event. It represents the existing catchment as presented in Figure 4.5 below.

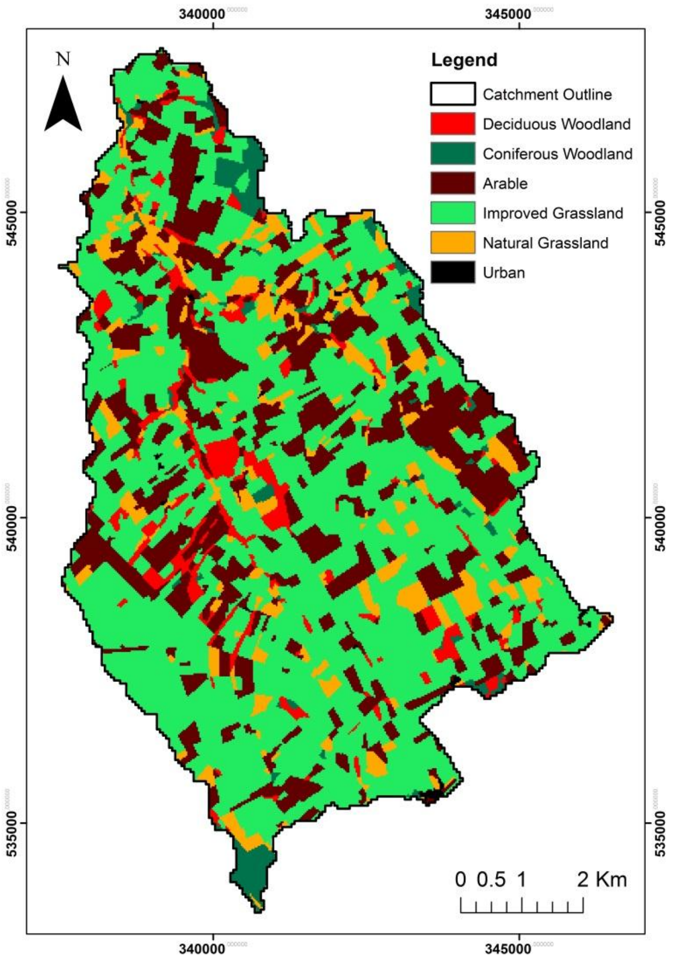

Figure 4.5 The simplified existing land cover in the River Roe catchment from which land cover change scenarios are created

4.3 Stakeholder engagement outcomes

Analysis of the semi-structured interviews and mapping exercise numerous potential solutions to solving flood risk using natural flood management interventions in the River Roe catchment emerged (Figure 4.6). All stakeholders agreed that there was scope for the implementation of a range of interventions suggesting large woody debris dams, river terrace planting, soil compaction management, surface runoff and infiltration management and bunds. Interventions that targeted land with little agricultural value, such as the wooded gills and becks located in the south west of the catchment, were preferred as the cooperation of farmers and landowners was deemed essential for the success of the project. The Environment Agency representative recommended the contribution of a chain of large woody debris dams and river terrace planting; targeting the attenuation of flow before it joins the main river channels. With regards to land management through land cover change, the use of infiltration and buffer strips was considered an option and was determined through the targeting of higher risk fields using the SCIMAP-Flood flood risk generation output. There was concern that land cover change scenarios would meet disapproval from land owners and farmers and anything requiring above a five percent loss of arable land or grassland would never be accepted without significant compensation; the rural nature of the catchment meant the maximised agricultural productivity is essential to protect the livelihoods of the local population.

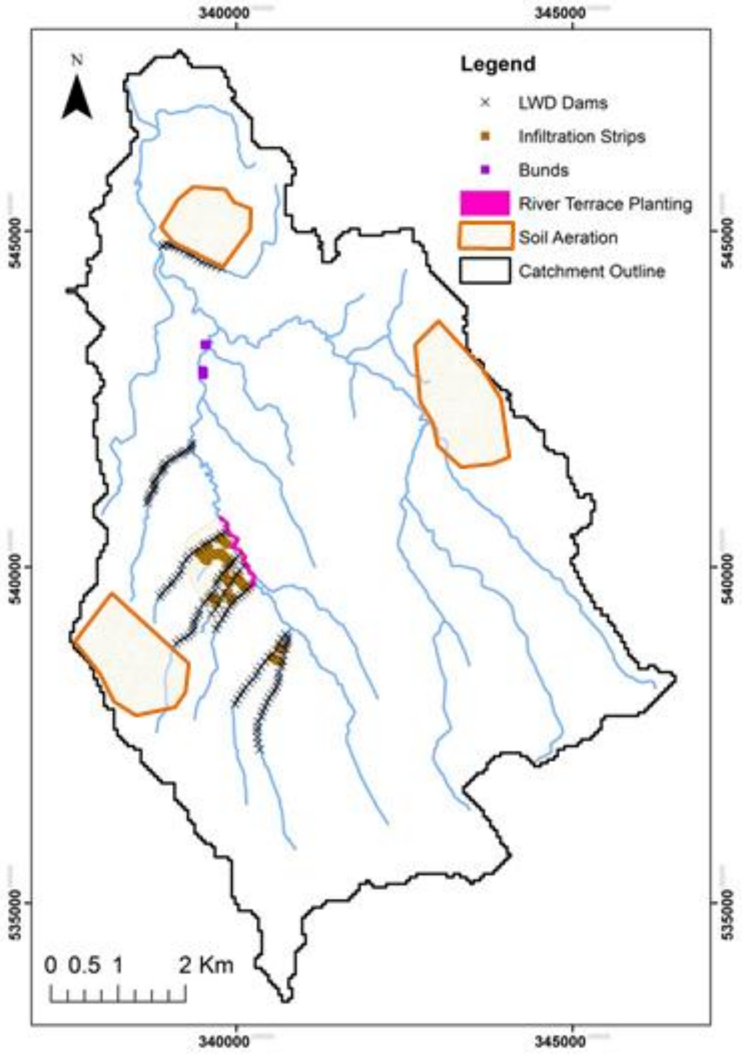

Figure 4.6 The collated results of the July 2015 mapping exercise with stakeholders collectively deciding potential locations for natural flood management interventions in the River Roe catchment.

A suggested alternative, that has a positive influence on agricultural output, was acting upon potential soil compaction problems. Soil aeration applied to the high flood generation risk areas on a field scale was encouraged, particularly by members of the Roe Catchment Community Water

Management Group. From the stakeholder engagement it was decided that targeted land cover change, soil aeration and large woody debris dams scenarios should be tested with CRUM3 and the modelled impact on flood risk reduction relayed to the stakeholders to be applied in the catchment.

4.4 Natural flood management scenarios

The assessment of land use management for flood risk reduction purposes was achieved by analysing the percentage change in the maximum discharge (MaxQ) at the location of the Environment Agency gauging station in Stockdalewath (Chapter 3). MaxQ is the maximum simulated discharge during the 2005 flood event and percentage change was calculated using the MaxQ from the land cover change scenario and the corresponding GLUE run MaxQ with the simplified LCM2007 land cover for each of the top 30 ranked GLUE runs. With the overall project aim being to reduce flood risk in the River Roe catchment, a reduction in MaxQ is the desired result. The full results for all the following modelled scenarios are shown at the end of this chapter in Table 4.2.

4.4.1 Blanket Coverage Scenarios

The first land cover change scenario modelled using CRUM3 was the blanket coverage scenario whereby the entire River Roe catchment was altered to complete coverage using each of the six land cover categories. Each of the top 30 GLUE model runs were simulated; scenarios simulating the impact from blanket coverage on MaxQ are presented in Figure 4.7.

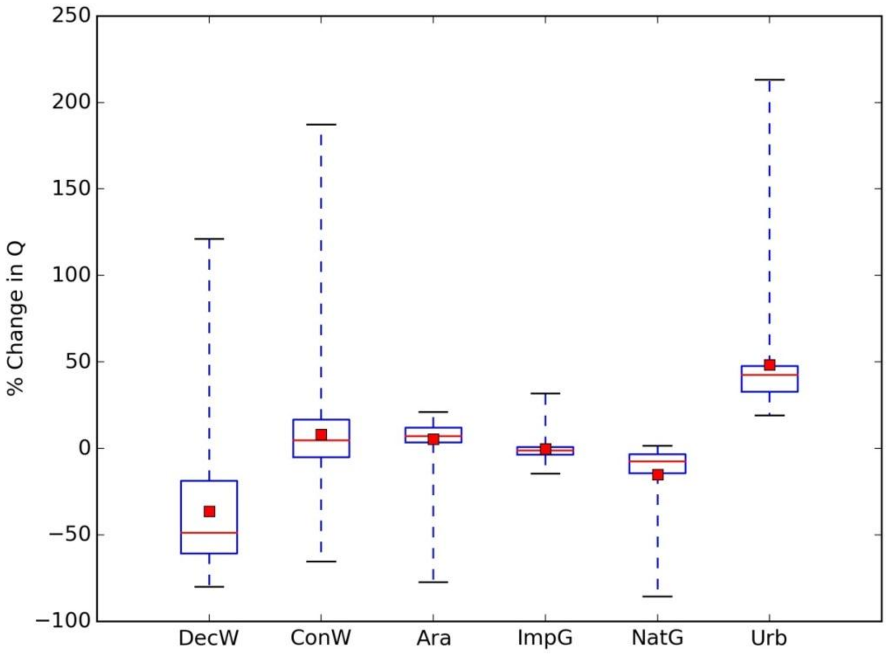

Figure 4.7 Blanket land cover change scenarios and the effect on MaxQ for the six land cover categories. The mean is represented by the red square and the median by the red line. 'DecW' is the deciduous woodland category, 'ConW' is coniferous woodland, 'Ara' is arable, 'ImpG' is improved grassland, 'NatG' is natural grassland and 'Urb' is urban.

The blanket deciduous woodland scenario had the greatest mean (-36.36%) and median (-48.92%) reduction in MaxQ for the 2005 flood event; the set of 30 parameter ensembles had the potential to reduce MaxQ by -80.04% or increase MaxQ by 120.95%. Of the 30 parameter sets 27 showed a MaxQ reduction of greater than 5%, 25 of greater than 10%, 21 of greater than 20%, 19 of greater than 30% and 18 of greater than 40%. The blanket coniferous woodland scenario had a mean increase in MaxQ of 8.18%, a median of a 4.65% MaxQ increase and a range between a -65% MaxQ decrease and a 187% MaxQ increase. Despite having numerous similar parameter values as derived from the literature there was a significant difference between the influence on maximum discharge resulting from blanket coverage of the two woodland categories. The greatest parameter value disparity occured with soil K_{SAT} and thus the variation in catchment response can be attributed to the saturated conductivity of the soil.

The second most effective land cover category with regards to MaxQ reduction under a blanket coverage scenario was natural grassland. There was a mean MaxQ reduction of -15.24%, a median reduction of -7.59% and a range between a MaxQ decrease of -85.76% and increase of 1.43%. 18 of the 30 parameter sets showed a MaxQ reduction of greater than 5%, 10 of greater than 10%, 4 of greater than 20%, 4 of greater than 30% and 4 of greater than 40%. The dominant existing land cover category, improved grassland, had a limited impact on the hydrological regime with a mean

MaxQ reduction of -0.28% and a median reduction of -1.11% under a blanket coverage land cover change scenario. Eleven of the 30 parameter sets exhibited a MaxQ reduction of greater than 2%, 5 of greater than 5% and one of greater than 10%. Additionally the arable land blanket coverage scenario had, predominantly, an increase on MaxQ with a mean increase of 5.37% and a median increase of 7.07%. The greatest MaxQ increase was 20.93% and only one parameter set produced a MaxQ reduction with a resultant -77.31% decrease in flow.

The urban land cover category produced the most significant increase in MaxQ for the 2005 flood event; this was to be expected with the simulated removal of all catchment vegetation. MaxQ increased between 19.13% and 213.09% with a mean increase of 48.39% and a median increase of 42.42%. With limited infiltration capacity through an impermeable layer, a lower overland flow friction factor and little storage in a thin soil layer water entered the channel network quickly in comparison to the other land cover categories.

Using blanket land cover change for flood risk reduction through land management has identified the relative effectiveness of the six land cover categories. The deciduous woodland scenario, whilst not a realistic option for implementation, gives an indication of the maximum reduction available through land cover change. The most consistently effective coverage options at reducing MaxQ for the 2005 flood event were deciduous woodland and natural grassland with both being utilised in scenarios in the subsequent sections.

4.4.2 Targeting land use change scenarios with SCIMAP Hydrological connectivity

4.4.2.1 Scenario development

Hydrological connectivity can be utilised to help target areas of high potential connection to the river channels with land use change to test the impact on flood risk reduction. Figure 4.8 shows a resampled (from 5m x 5x cell size to 50m x 50 cell size using the raster resample tool on ArcGIS obtaining the average connectivity value for each cell) hydrological connectivity risk map from SCIMAP for the River Roe catchment. The blue highlights hydrologically disconnected areas and the red denotes areas that are most connected. The connectivity risk map was used to create five land cover change scenarios through changing the land cover above risk values of 0.5 (98.01% land cover change), 0.6 (89.65%), 0.7 (70.82%), 0.8 (41.30%) and 0.9 (19.14%). Values below 0.5 were considered too similar to the blanket coverage scenarios and weren't considered for scenario testing. The aforementioned land cover was altered to both deciduous woodland and natural grassland. Examples of the updated land cover in the modelled scenarios are given for deciduous woodland above 0.6 (Figure 4.9a) and 0.8 (Figure 4.9b).

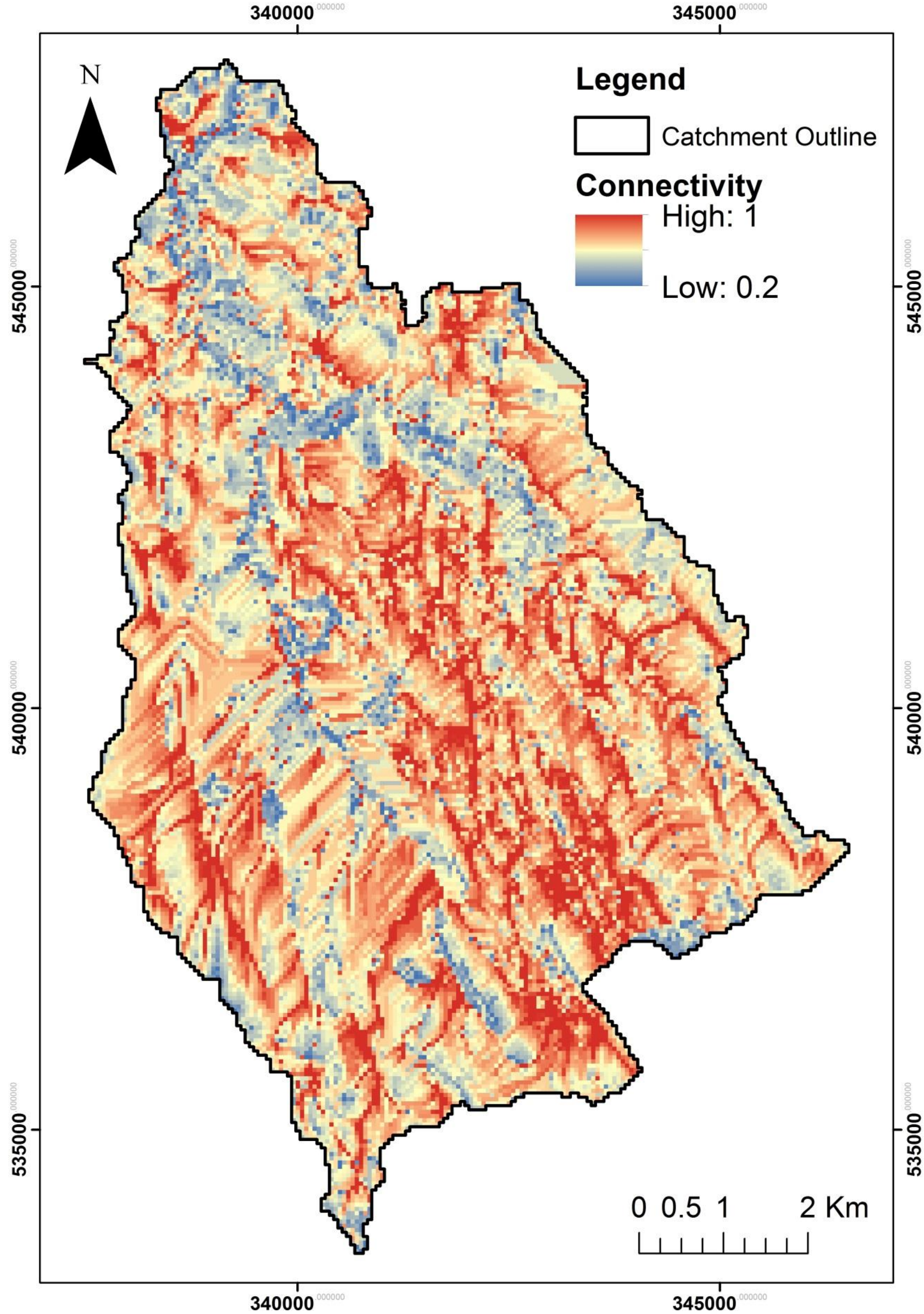

Figure 4.8 SCIMAP Hydrological connectivity relative risk map.

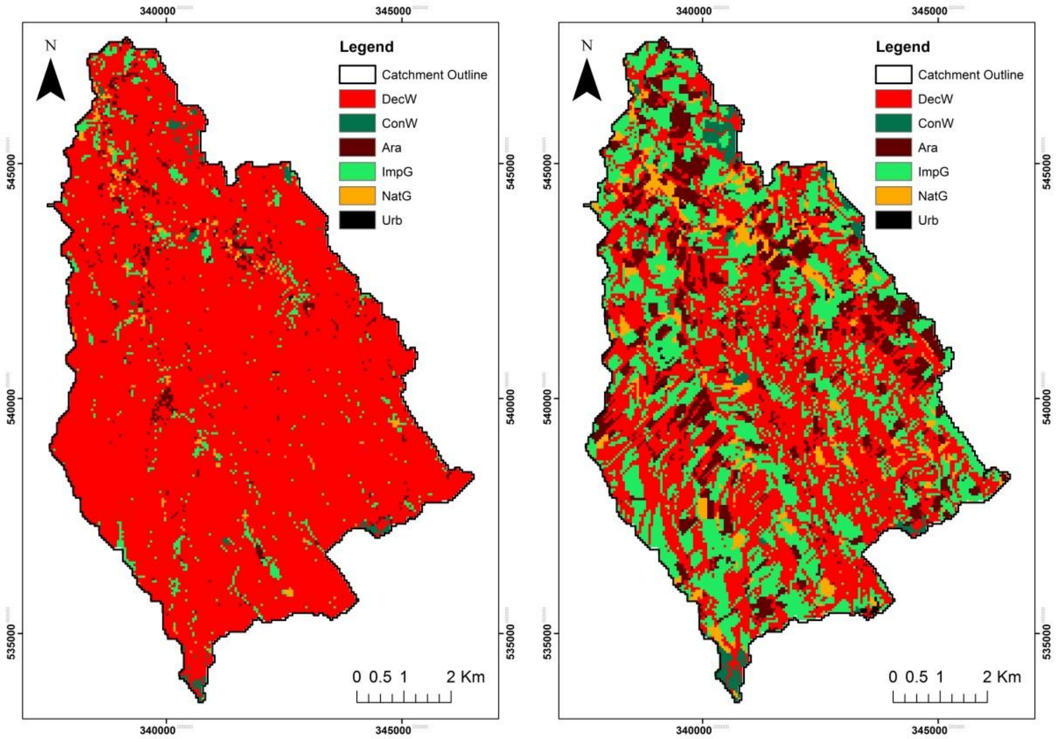

Figure 4.9a&b Catchment land cover generated from SCIMAP hydrological connectivity output with (a) deciduous woodland above 0.6 and (b) deciduous woodland above 0.8. 'DecW' is the deciduous woodland category, 'ConW' is coniferous woodland, 'Ara' is arable, 'ImpG' is improved grassland, 'NatG' is natural grassland and 'Urb' is urban.

4.4.2.2 Hydrological connectivity based land cover change scenario results

The results from the hydrological connectivity based land cover change scenarios for change to both deciduous woodland and natural grassland for the top 30 ranked GLUE runs are shown in Figure 4.10 and 4.11 respectively. There is a trend using both deciduous woodland and natural grassland towards zero percentage change as the amount of area assigned to land cover change lessens; the scenarios grow closer to the existing catchment land cover. In both categories of land cover change the variation between the mean and median and the range within the 30 model runs diminishes as the area of land cover changed is reduced. This effect is a result of an increased area of altered soil and land cover parameters reacting to the parameter value change from the new land cover.

With a proposed 98.01% and 89.65% of the catchment area to be altered both the above 0.5 and 0.6 scenarios have similar results to the corresponding blanket coverage scenarios from Section 4.4.1; a mean reduction in MaxQ of -35.38% and -34.71% for deciduous woodland and -13.9% and -13.31% for natural grassland respectively. Additionally the above 0.7 scenario results in a mean of -33.19% using deciduous woodland despite requiring 18.83% less land cover change than the above 0.6 scenario; this would evidence the targeting of connected areas using SCIMAP output areas can have a beneficial impact on selecting areas for land cover change. The predicted reduction in MaxQ from natural grassland land cover change produced a mean of -10.88% from the 30 model runs.

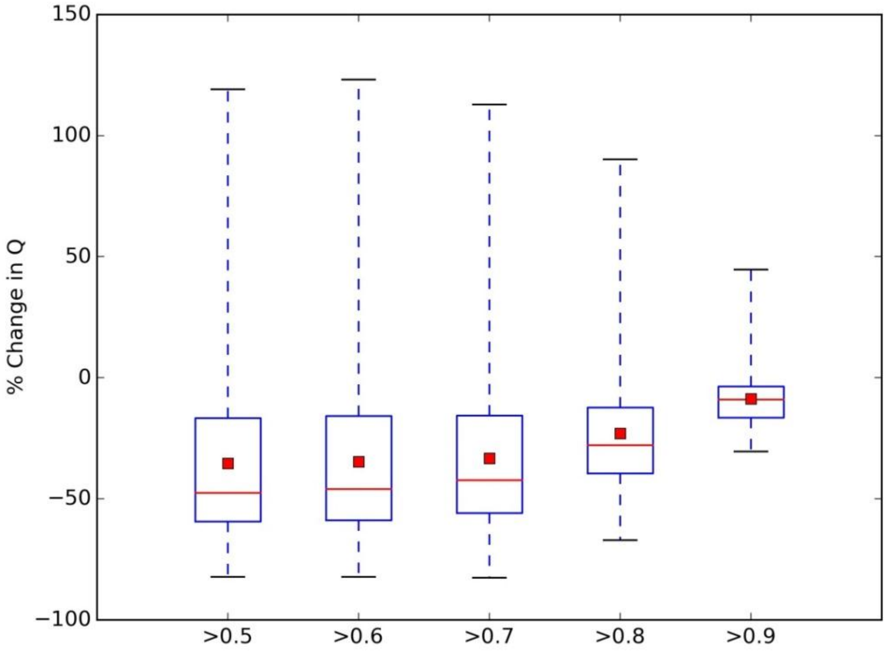

Figure 4.10 Hydrological connectivity based land cover change scenarios from SCIMAP using deciduous woodland and the effect on MaxQ. The mean is represented by the red square and the median by the red line.

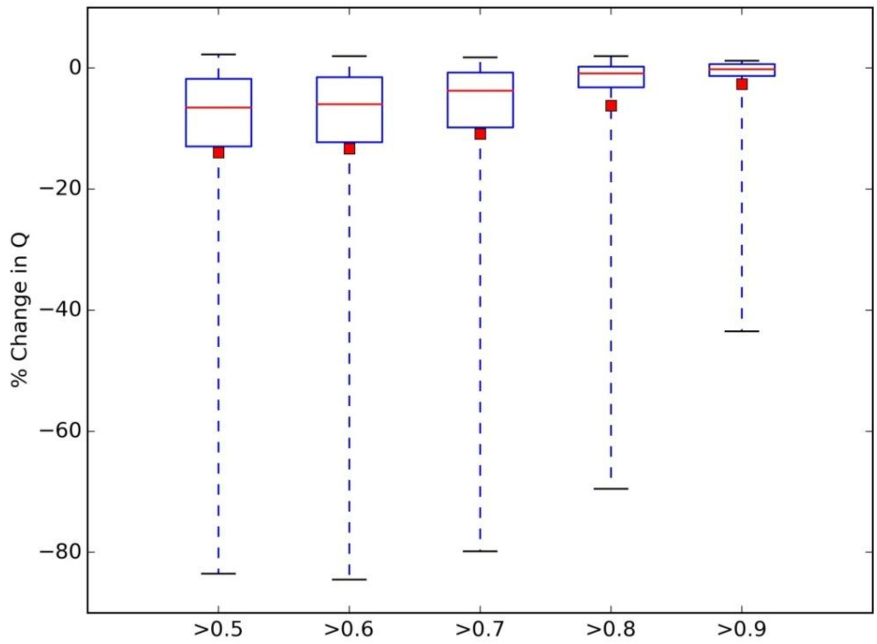

Figure 4.11 Hydrological connectivity based land cover change scenarios from SCIMAP using natural grassland and the effect on MaxQ. The mean is represented by the red square and the median by the red line.

The scenarios for land use change above 0.8 and 0.9 from the hydrological connectivity SCIMAP output are more feasible for implementation and require less land adjustment. For the addition of deciduous woodland at the relative high risk points in the River Roe catchment land change above 0.8 and 0.9 there is a potential mean (-22.98% and -8.71%) and median (-27.79% and -8.97%) reduction in MaxQ for the 2005 flood event; the set of 30 parameter ensembles had the potential to reduce MaxQ by -67.05% and -30.55%. Land use change to natural grassland above 0.8 and 0.9 produced a potential mean (-6.17% and -2.62%) and median (-0.92% and -0.23%) reduction in MaxQ for the 2005 flood event; the set of 30 parameter ensembles had the potential to reduce MaxQ by -69.54% and -43.48%.

4.4.3 Targeting land use change scenarios with SCIMAP flood risk generation

4.4.3.1 Scenario development

Figure 4.12 shows a resampled (from 5m x 5x cell size to 50m x 50 cell size using the raster resample tool on ArcGIS) flood risk generation map from SCIMAP for the River Roe catchment. Blue highlights areas of low flood risk generation and the red areas that exhibit the greatest relative flood risk generation values. The flood risk generation map was used to create nine land cover change scenarios through changing the land cover above risk values of 0.1 (30.57% catchment land cover change), 0.2 (12.41%), 0.3 (6.75%), 0.4 (3.76%), 0.5 (1.79%), 0.6 (0.65%), 0.7 (0.15%), 0.8 (0.03%) and 0.9 (0.01%). Whilst values above 0.6 have less than one percent land coverage they represent the areas of highest flood risk generation and thus the scenarios were modelled using CRUM3. The aforementioned land cover above the relevant threshold was altered to both deciduous woodland and natural grassland. Examples of the updated land cover in the modelled scenarios are given for deciduous woodland above 0.2 (Figure 4.13a) and 0.3 (Figure 4.13b).

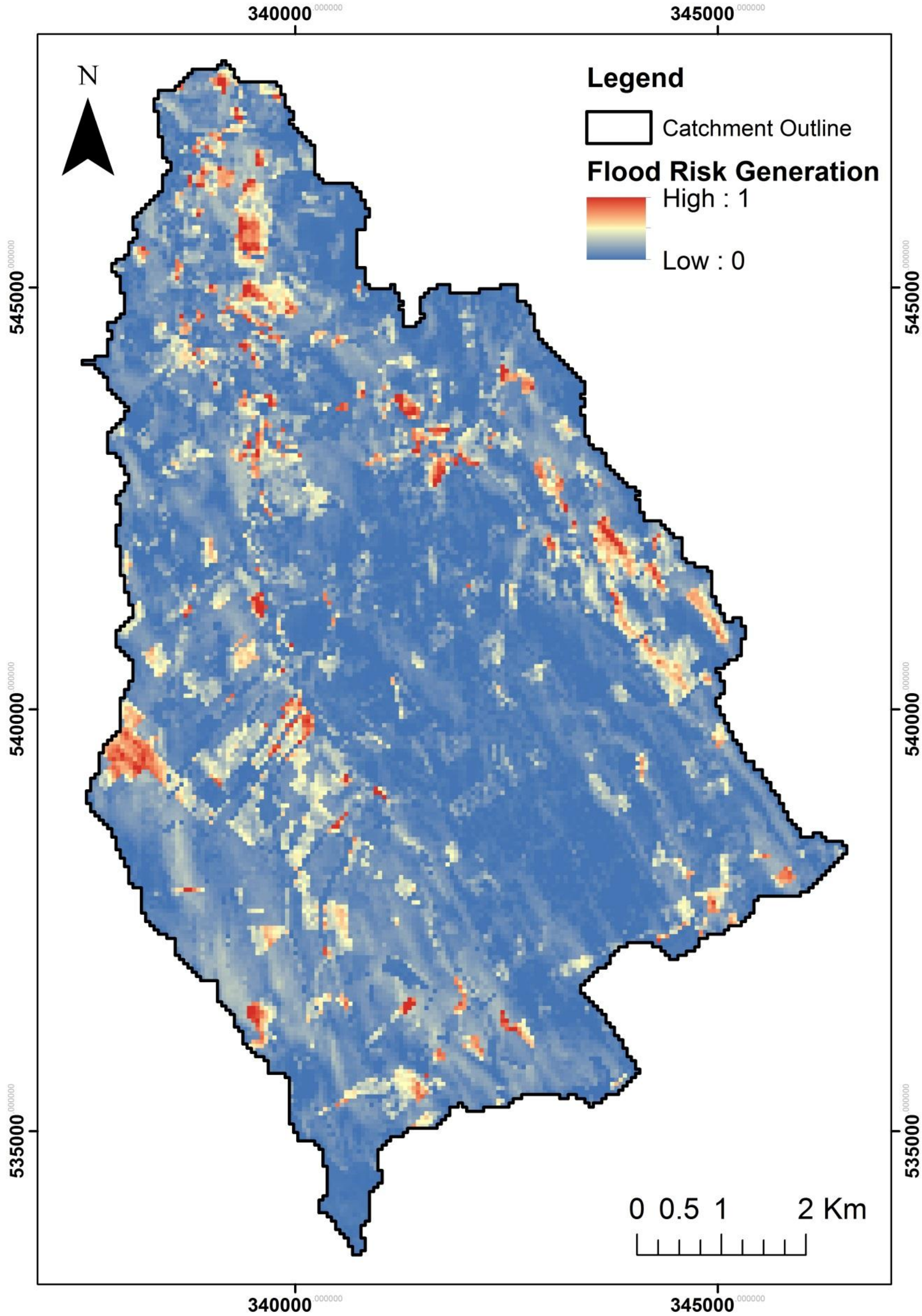

Figure 4.12 SCIMAP Flood risk generation relative risk map.

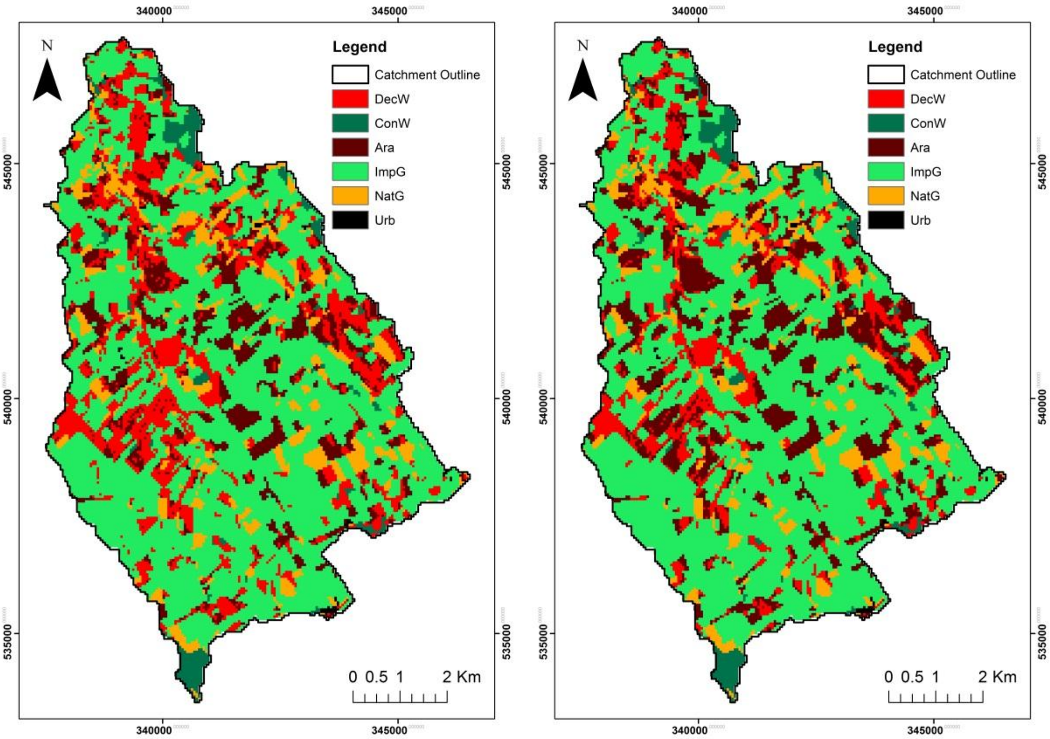

Figure 4.13a&b Catchment land cover generated from SCIMAP flood risk generation output with (a) deciduous woodland above 0.2 and (b) deciduous woodland above 0.3. 'DecW' is the deciduous woodland category, 'ConW' is coniferous woodland, 'Ara' is arable, 'ImpG' is improved grassland, 'NatG' is natural grassland and 'Urb' is urban.

4.4.3.2 Results from land cover change scenarios

The results from the flood risk generation based land cover change scenarios for both deciduous woodland and natural grassland for the top 30 ranked GLUE runs are shown in Figure 4.14 and 4.15. As with the hydrological connectivity based land cover change scenarios above, the flood risk generation based scenarios with less land devoted to deciduous woodland and natural grass alteration exhibited a lesser reduction in MaxQ. Similarly both categories of land cover change displayed a decreased variation between the mean and median and the range within the 30 model runs as the area of land cover changed was decreased.

The maximum reduction in MaxQ for the 30 model sets occurred under the above 0.1 deciduous woodland cover change scenario which had a mean MaxQ reduction of -11.65% and a median reduction of -15.49%. The corresponding 0.1 natural grassland cover change scenario has a mean MaxQ reduction of -4.78% and a median reduction of -3.79%; this was a lower mean and median reduction in MaxQ than the above 0.2 deciduous woodland scenario (-4.05% and -6.61%) suggesting that converting 12.41% of the catchment to deciduous woodland would be a more effective flood risk reduction solution than a 30.57% area conversion to natural grassland.

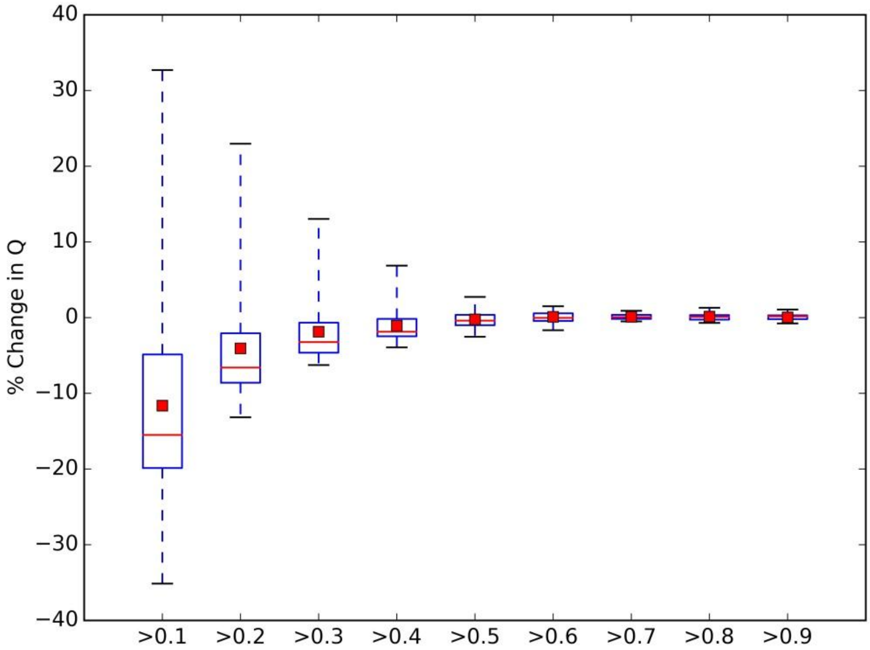

Figure 4.14 Flood risk generation based land cover change scenarios from SCIMAP using deciduous woodland and the effect on MaxQ. The mean is represented by the red square and the median by the red line.

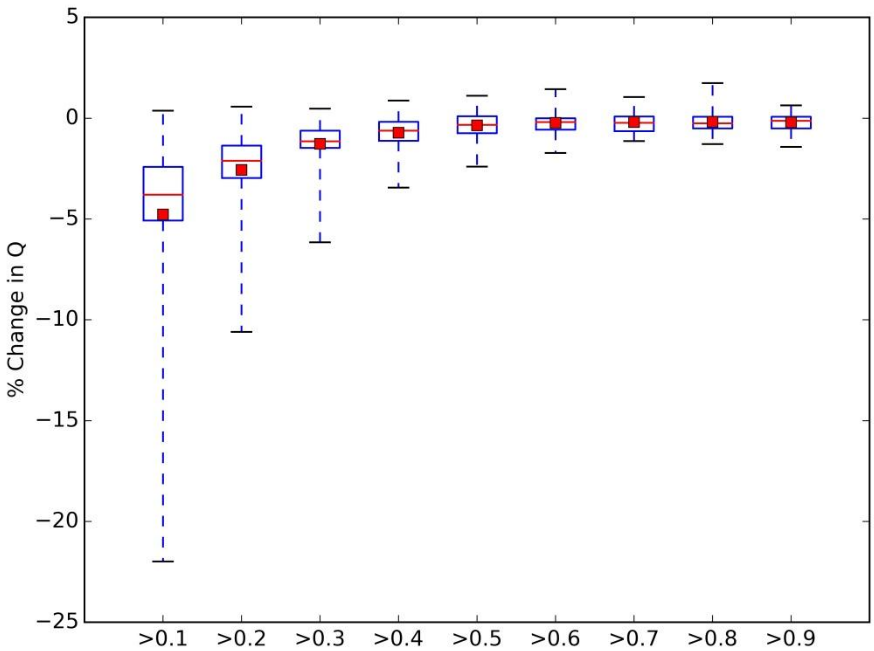

Figure 4.15 Flood risk generation based land cover change scenarios from SCIMAP using natural grassland and the effect on MaxQ. The mean is represented by the red square and the median by the red line.

The scenarios developed for land cover change above 0.3 and 0.4 represented the most viable flood risk reduction options to be implemented at a catchment scale with a proposed area of 3.76% and 6.75%. The above 0.3 scenario for deciduous woodland and natural grassland land cover change had a mean reduction in MaxQ of -1.88% and -1.27% and a median reduction of -3.23% and -1.15% correspondingly; both land cover change scenarios have a maximum reduction of above -6% (-6.25% and -6.15%). The above 0.4 scenario for deciduous woodland and natural grassland land cover change had a mean reduction in MaxQ of -1.06% and -0.72% and a median reduction of -1.86% and -0.62%.

The land cover change scenarios based on flood risk generation values above 0.6, 0.7, 0.8 and 0.9 altered less than two percent of the catchment land cover and for both the deciduous woodland and natural grassland scenarios had little impact on MaxQ despite concentrating on the areas with the highest flood risk generation values. There was a maximum reduction in MaxQ of -1.65%, -0.49%, -0.68% and -0.77% respectively for the deciduous woodland land cover change with the mean values all showing an increase in MaxQ of less than 0.1%. Using natural grassland land cover change there was maximum reduction of -1.72%, -1.14%, -1.28% and -1.42% and mean and median MaxQ reductions concentrated on -0.2%. This result highlights that when targeting minimal land cover change for flood risk reduction purposes it is more effective to alter the existing land to natural grassland.

4.4.4 Field scale land cover change scenarios

4.4.4.1 Scenario development

The previous scenarios have utilised SCIMAP output to target land cover change on areas of high connectivity and flood risk generation without fully considering the practicality in applying a given scenario in the catchment. The hydrological connectivity and flood risk generation scenarios failed to consider existing field boundaries within the catchment and had variable land coverage at a field scale. To create a more realistic flood risk reduction scenario land cover change was implemented at a field scale and informed using the SCIMAP flood risk generation output used in the previous section.

Field scale land cover change scenarios were developed using the SCIMAP flood risk generation categories superimposed on Ordnance Survey 1:25,000 vector data; the OS data shows the existing field boundaries in the River Roe catchment. Fields with greater than 50% cover above the set flood risk generation value were selected for land cover change to deciduous woodland and natural grassland. This process was completed for the flood risk generation values above 0.1 (27.97% catchment land cover change), 0.2 (12.38%), 0.3 (5.91%), 0.4 (2.36%), 0.5 (1.06%), 0.6 (0.09%) and

0.7 (0.03%); values above 0.8 and 0.9 had no fields with greater than 50% coverage and thus were not used. The 0.2 category is used to showcase this scenario development; Figure 4.16a highlights the fields with an above 0.2 flood risk generation value and Figure 4.16b shows the final field scale land cover change scenario for deciduous woodland.

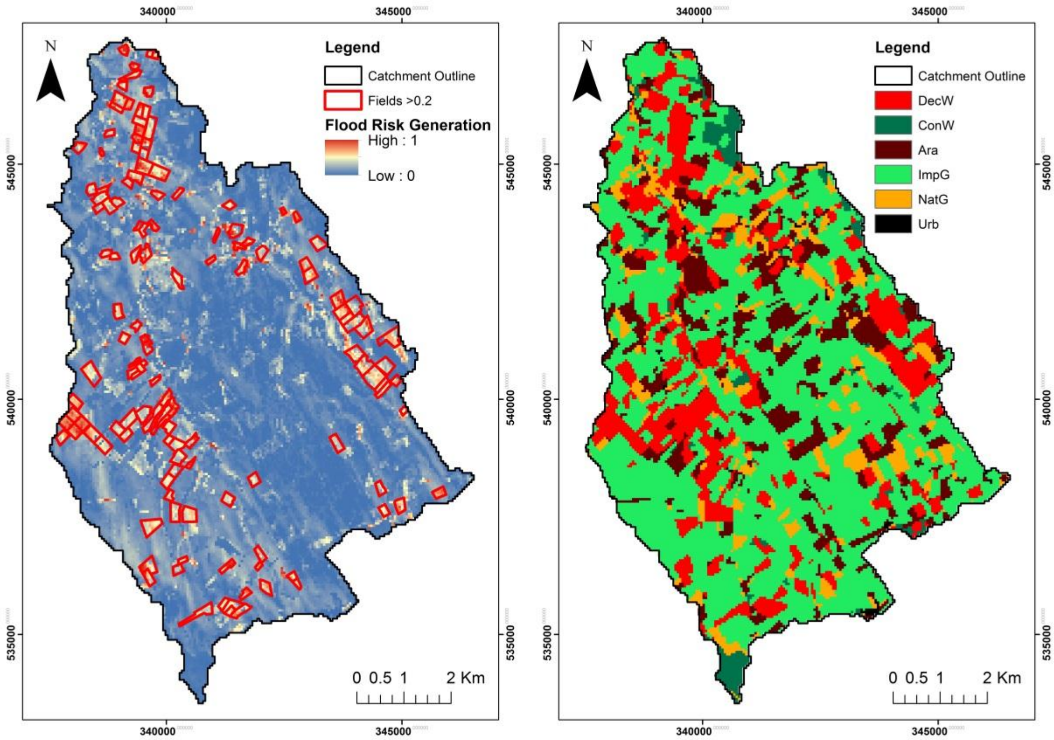

Figure 4.16a&b (a) SCIMAP Flood risk generation relative risk map with fields having greater than 50% coverage of above 0.2 flood risk generation value highlighted in red. (b) The above 0.2 field scale land cover change scenario using deciduous woodland. 'DecW' is the deciduous woodland category, 'ConW' is coniferous woodland, 'Ara' is arable, 'ImpG' is improved grassland, 'NatG' is natural grassland and 'Urb' is urban.

4.4.4.2 Field scale land cover change scenario results

Figure 4.17 demonstrates the results of the 30 model runs show the greatest reduction in MaxQ using field scale land cover change with the above 0.1 and 0.2 deciduous woodland change scenarios; this was also observed in the SCIMAP flood risk generation based scenarios in section 4.4.4. The mean MaxQ reduction was -12.09% and -4.89% and the median MaxQ reduction was -15.72% and -7.22% respectively. The corresponding natural grassland change scenarios (Figure 4.18) showed a mean and median MaxQ reduction of -4.24% and -2.77% for the 0.1 scenario and -1.97% and -1.61% for the 0.2 scenario. Using the maximum percentage change in MaxQ from the modelled 30 parameter sets there is the potential for a -31.77% reduction with the above 0.1 deciduous woodland land cover change scenario and a -22.41% reduction with the above 0.1 natural grassland land cover change scenario. Land cover change to deciduous woodland and natural grassland for the above 0.3 scenario had a mean reduction in MaxQ of -1.10% and -0.64% and a median reduction of -

2.45% and -0.49%; 18 of the 30 model runs showed a greater than 2% MaxQ reduction for deciduous woodland scenario and 3 of the 30 for natural grassland.

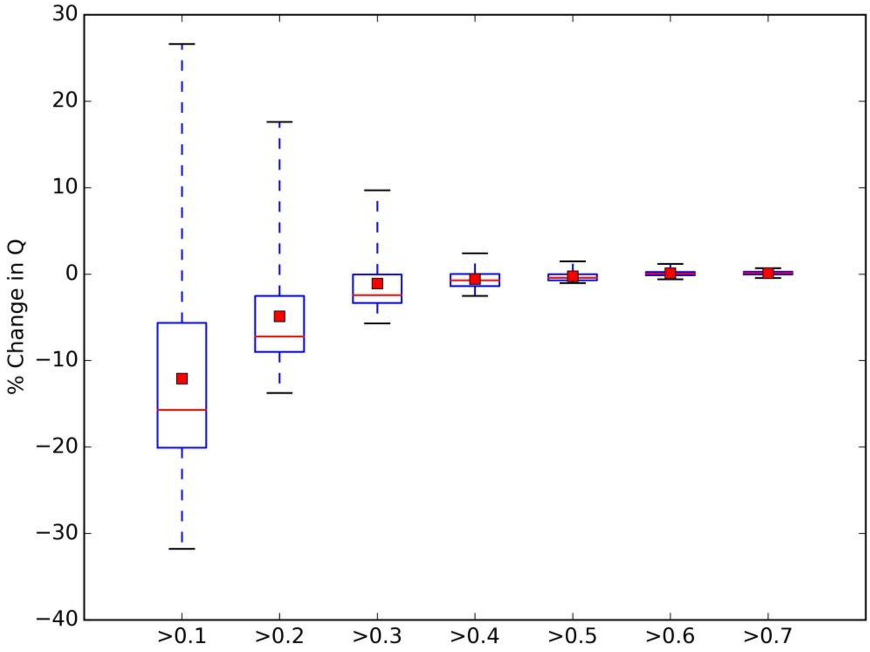

Figure 4.17 Field scale land cover change scenarios using deciduous woodland

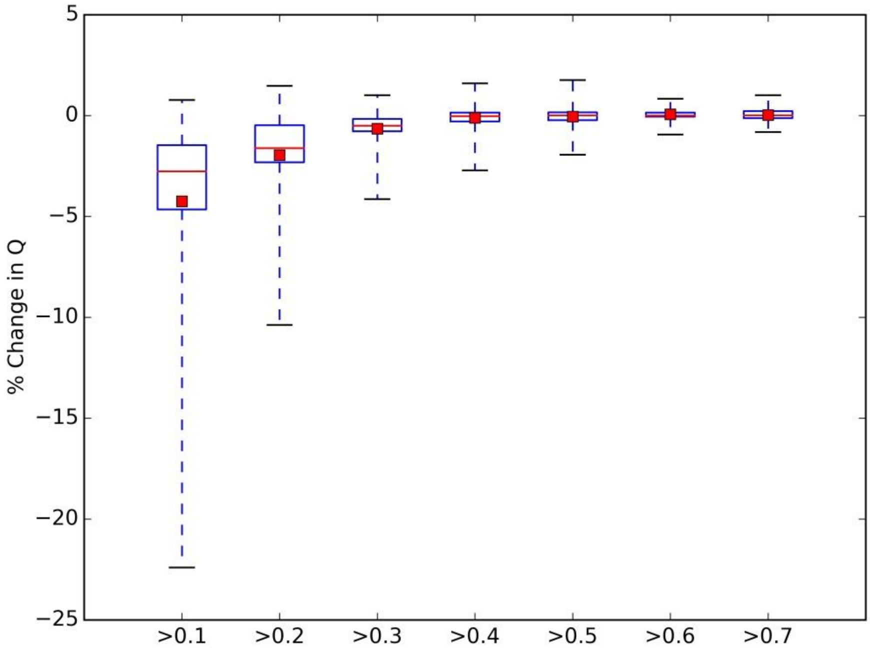

Figure 4.18 Field scale land cover change scenarios using natural grassland

The above 0.4, 0.5, 0.6 and 0.7 field scale land cover change scenarios for both deciduous woodland and natural grassland has a less than -0.6% mean reduction in MaxQ and a less than -0.7% median reduction in MaxQ. These scenarios offer limited value with regards to a possible flood risk reduction in the River Roe catchment.

4.4.5 Field buffer zone scenarios

4.4.5.1 Scenario development

Using the same data and field selection process outlined in section 4.4.4 scenarios were developed with deciduous woodland and natural grassland field buffers; this allowed CRUM3 to simulate both woodland shelter belts and field buffer strips, targeting areas of high flood risk generation (Environment Agency, 2012). The creation of buffers around field boundaries allows the continuation of agricultural practice in the field and limits the potential loss of productive land that the field scale land cover change scenarios would cause.

Fields with greater than 50% cover above the set flood risk generation value were selected for the addition of a 25m buffer using both deciduous woodland and natural grassland. A 25m buffer was the minimum width that could be used with the CRUM3 model operating using a 50m x 50m cell size; a single cell represents a 25m buffer zone either side of the field boundary. This process was completed for the flood risk generation values above 0.1 (15.54% catchment land cover change), 0.2 (7.18%), 0.3 (3.59%), 0.4 (1.46%), 0.5 (0.67%), 0.6 (0.07%) and 0.7 (0.03%); values above 0.8 and 0.9 had no fields with greater than 50% coverage and thus were not used. The 0.2 category was used to illustrate this scenario development. Figure 4.19a shows the fields with an above 0.2 flood risk generation value and Figure 4.19b highlights the 25m field buffer scenario using deciduous woodland.

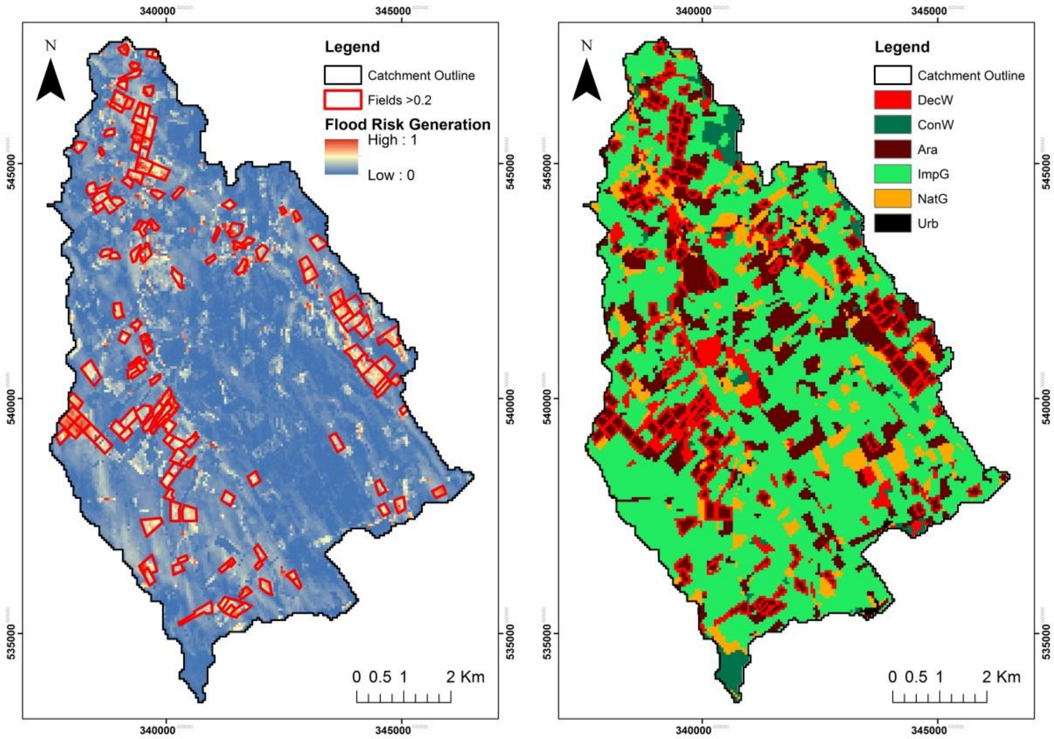

Figure 4.19a&b (a) SCIMAP Flood risk generation relative risk map with fields having greater than 50% coverage of above 0.2 flood risk generation value highlighted in red. (b) The above 0.2 25m field buffer scenario using deciduous woodland. 'DecW' is the deciduous woodland category, 'ConW' is coniferous woodland, 'Ara' is arable, 'ImpG' is improved grassland, 'NatG' is natural grassland and 'Urb' is urban.

4.4.5.2 Field buffer scenario results

The results for the 30 model runs using the field buffer scenarios are shown in Figure 4.20 and 4.21 below. Following the trend from the previous modelled scenarios there is a decrease in MaxQ reduction as the area of land cover is reduced. There is a similar pattern in MaxQ reduction to the field scale land cover change scenarios with the above 0.1 deciduous woodland buffer scenario displaying the greatest reduction in MaxQ ; the scenario had a mean MaxQ reduction of -5.07% and median of -7.78%. The mean and median reduction in MaxQ for the above 0.2 deciduous woodland field buffer scenarios is -1.82% and -3.34%. For the corresponding above 0.1 and 0.2 natural grassland field buffer zone scenarios the mean reduction in MaxQ was -1.96% and -0.85% and a median of -1.16% and -0.31%. The maximum reduction from the 30 model runs was -20.65% and -7.78% for the deciduous woodland scenarios and -18.23% and -8.35% for the natural grassland scenarios.

The above 0.3, 0.4, 0.5, 0.6 and 0.7 field scale land cover change scenarios for both deciduous woodland and natural grassland has a less than -0.3% mean reduction in MaxQ and, other than the above 0.3 deciduous woodland scenario which had a median reduction of -1.08%, a median reduction in MaxQ of less than 0.17%. These scenarios offer limited value with regards to a possible flood risk reduction in the River Roe catchment.

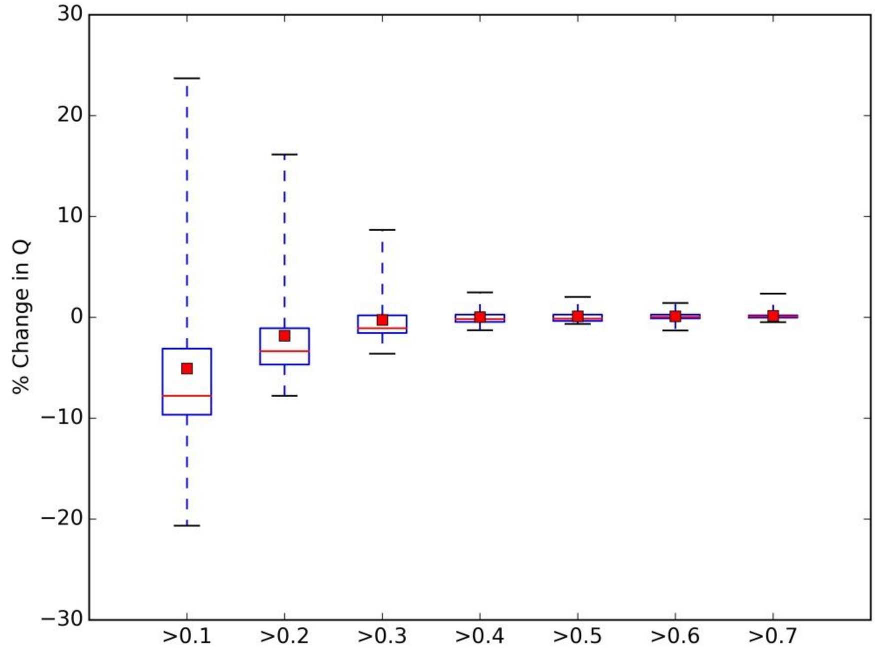

Figure 4.20 Field buffer zone scenarios using deciduous woodland

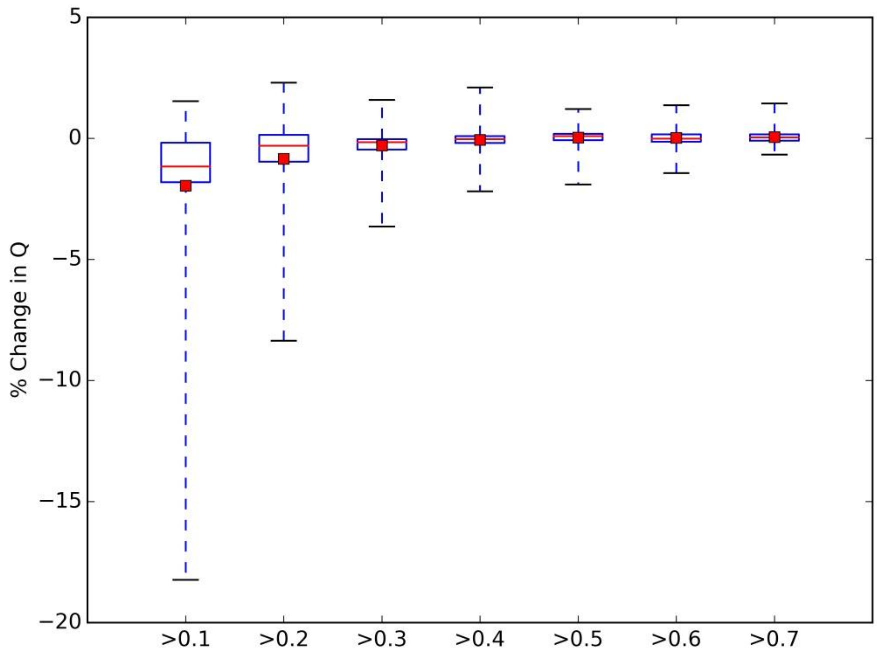

Figure 4.21 Field buffer zone scenarios using natural grassland

The impact of a deciduous woodland buffer zone on flood risk reduction appeared to be less efficient than the field scale land cover change using the comparison of catchment land cover area alteration and corresponding MaxQ reduction; the 15.54% change for the above 0.1 scenario has a similar impact on MaxQ reduction (mean values of -5.07% and -4.80% respectively) when compared to the field scale land cover change above 0.2 scenario (12.38% land cover change). The natural grassland field buffer zones showed a comparable trend which could be attributed to the field scale land cover change altering larger areas of associated soil parameters which store more infiltrated runoff in the soil and increase the area of slowed overland flow through vegetation modification.

4.4.6 Riparian buffer zone scenarios

4.4.6.1 Scenario development

Riparian buffer zones are a common land management techniques used to slow overland flow before it enters the channel network and predominantly comprised of woodland or natural grassland; they are normally between 1 and 50 metres wide (Environment Agency, 2012). Two riparian buffer zone scenarios were created for both deciduous woodland and natural grassland using buffer zone widths of 25m and 50m. The land cover scenarios created using deciduous woodland are shown in Figure 4.22a and 4.22b for the 25m and 50m buffer respectively. The 25m buffer requires 10.81% of the existing catchment land cover to be changed and the 50m buffer requires 20.59%.

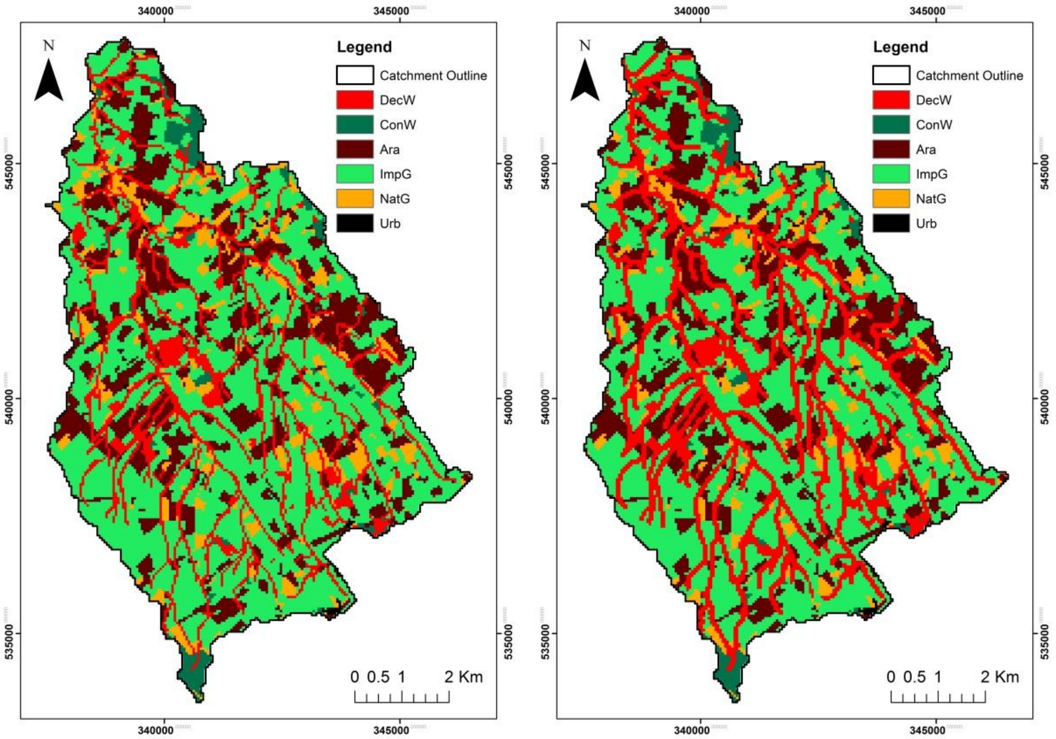

Figure 4.22a&b (a) The 25m riparian buffer zone land cover change scenario using deciduous woodland. (b) The 50m riparian buffer zone land cover change scenario using deciduous woodland. 'DecW' is the deciduous woodland category, 'ConW' is coniferous woodland, 'Ara' is arable, 'ImpG' is improved grassland, 'NatG' is natural grassland and 'Urb' is urban.

4.4.6.2 Riparian buffer zone results

The 30 model run results for both the 25m and 50m riparian buffer zone scenarios using both deciduous woodland and natural grassland are shown in Figure 4.23. The deciduous woodland buffer zone scenarios were the most effective at reducing MaxQ with the 50m buffer zone having a mean and median MaxQ reduction of -11.98% and -11.40% whilst the 25m buffer zone had a corresponding -5.23% and -4.59% MaxQ decrease. The natural grassland buffer zone scenarios were significantly less effective at reducing MaxQ in the River Roe catchment with the 50m buffer zone having a mean MaxQ reduction of -1.49% whereas the 25m buffer zone had a mean -0.47% MaxQ decrease. The median values for both the natural grassland scenarios with the 30 model runs showed a slight increase in MaxQ of 0.15% for the 50m buffer zone and 0.21% for the 25m buffer zone. Doubling the width of the buffer zone for both natural grassland and deciduous woodland land cover change returned a greater than double mean percentage reduction in MaxQ.

The maximum MaxQ reduction from the 30 model sets was -29.45% with the 50m natural grassland riparian buffer zone scenario; the 50m deciduous woodland buffer zone had a maximum reduction of -26.62%. With the 25m buffer zone scenarios the greatest reduction was -15.33% for natural grassland and -15.53% for deciduous woodland.

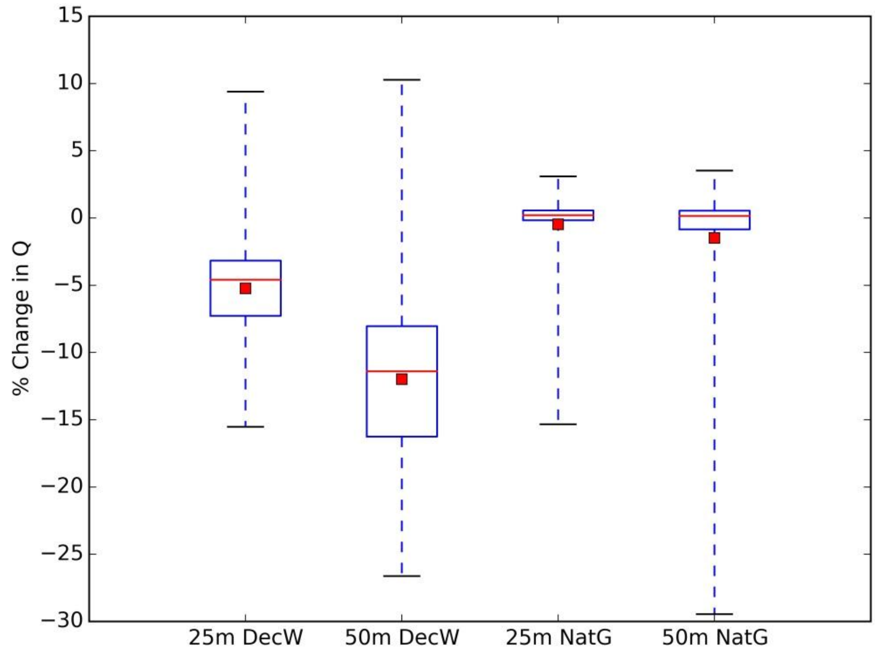

Figure 4.23 The 25m and 50m riparian buffer zone scenarios for both deciduous woodland ('DecW') and natural grassland ('NatG') land cover change.

4.4.7 Soil aeration scenarios

4.4.7.1 Soil parameter development

Three levels of soil compaction, light, medium and heavy, were chosen for soil parameter representation following soil compaction studies using CRUM3 carried out by Pattison (2010) and Smith (2011). Three compaction relationships were employed; heavy to medium, heavy to light and medium to light compaction. The catchment was assumed to have either medium compaction or heavy compaction levels dependent on the scenario with changed soil parameters applied to represent soil aeration. The altered parameters were applied to the existing soil parameters for the improved grassland and arable land cover categories from the 30 model sets and developed into flood risk reduction scenarios. The improved and arable land covers were considered essential for agricultural productivity; they are the most likely categories to experience soil compaction and were the only land covers where soil aeration can be implemented.

4.4.7.2 Scenario development

Two sets of scenarios were developed to assess the impact of soil aeration at reducing flood risk in the River Roe catchment; land cover targeted aeration and field scale flood risk generation driven aeration. These scenarios were created for assumed heavy compaction levels aerated to medium compaction levels, assumed heavy compaction levels aerated to light compaction levels and assumed medium compaction levels aerated to light compaction levels.

The first set of scenarios altered the entire area of the arable and improved grassland land cover categories from their assumed current compact level to an aerated compaction level; this was done with three scenarios using all the arable area (23.91% catchment area to be aerated), all the improved grassland area (58.54%) and the combined arable and improved grassland area (82.45%). The second set of aeration scenarios used the same process outlined in section 5.4 to establish fields with the high flood risk generation values based from SCIMAP output; this was completed for flood risk generation values above 0.1 (27.97% catchment area to be aerated), 0.2 (12.38%), 0.3 (5.91%), 0.4 (2.36%), 0.5 (1.06%), 0.6 (0.09%) and 0.7 (0.03%). As opposed to the field scale land cover change in section 4.4.4 the scenarios were developed to quantify the impact of aerating the soil in the specified fields.

4.4.7.3 Land cover targeted soil aeration results

The results for the land cover targeted soil aeration scenarios for the top 30 ranked model runs are shown in Figure 4.24. As was evident with the previous land cover change scenarios the greater the amount of catchment area assigned to soil aeration application, the greater the reduction in MaxQ. Though unrealistic in their usage as a flood risk reduction technique due to the required area to be aerated and the unlikeliness that the entire catchment will be compacted, the use of soil aeration has a significant impact on the MaxQ in the River Roe catchment.

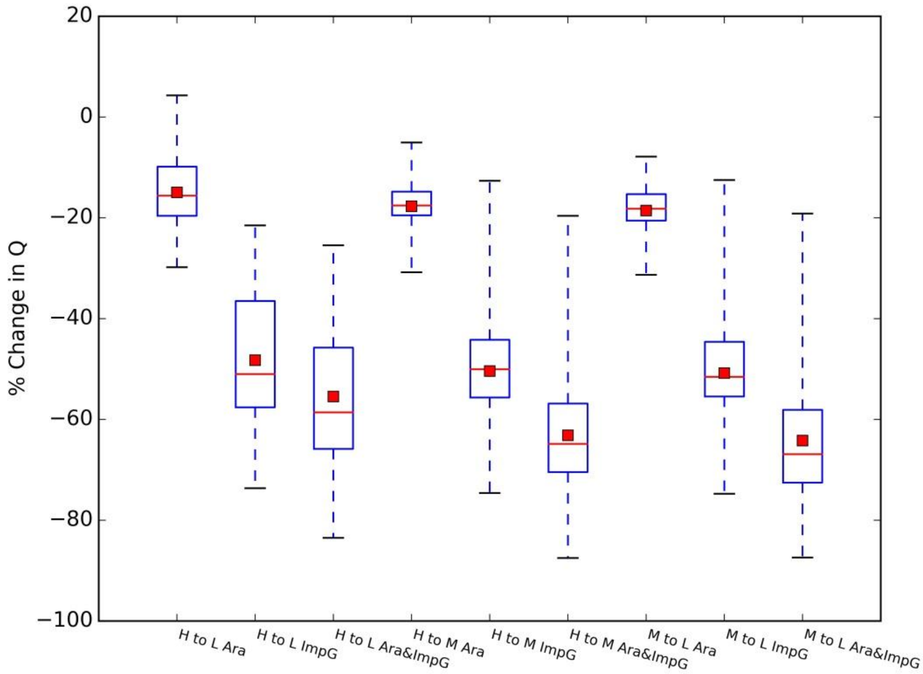

Figure 4.24 The MaxQ percentage change using the land cover targeted soil aeration scenarios. 'H' refers to heavy compaction levels, 'M' to medium compaction levels and 'L' to light compaction levels. 'Ara' is the arable land cover category and 'ImpG' is the improved grassland land cover category.

Applying soil aeration techniques until the soil is at the light compaction level to an assumed existing heavy compaction level across both the improved grassland and arable land cover in the catchment returned a mean and median reduction in MaxQ of -55.47% and -58.62%. Achieving a medium compaction level from an existing high compaction level had a mean and median reduction in MaxQ of -63.13% and -64.86% and moving from a medium compaction level to a light compaction level had a mean MaxQ reduction of -64.19% and median of -66.89%.

Aerating the arable land in the catchment had a mean reduction in MaxQ of -14.93% going from a heavy to light soil compaction level, -17.70% from a heavy to medium soil compaction level and -18.53% from a medium to light soil compaction level. Completing soil aeration to the catchment improved grassland land cover had a mean reduction in MaxQ of -48.26% going from a heavy to light soil compaction level, -50.38% from a heavy to medium soil compaction level and -50.79% from a medium to light soil compaction level.

4.4.7.4 Field scale flood risk generation driven aeration results

The field scale flood risk generation driven aeration results are given in Figure 4.25 (assumed heavy to light compaction levels), 4.26 (assumed heavy to medium compaction levels) and 4.27 (assumed medium to light compaction levels).

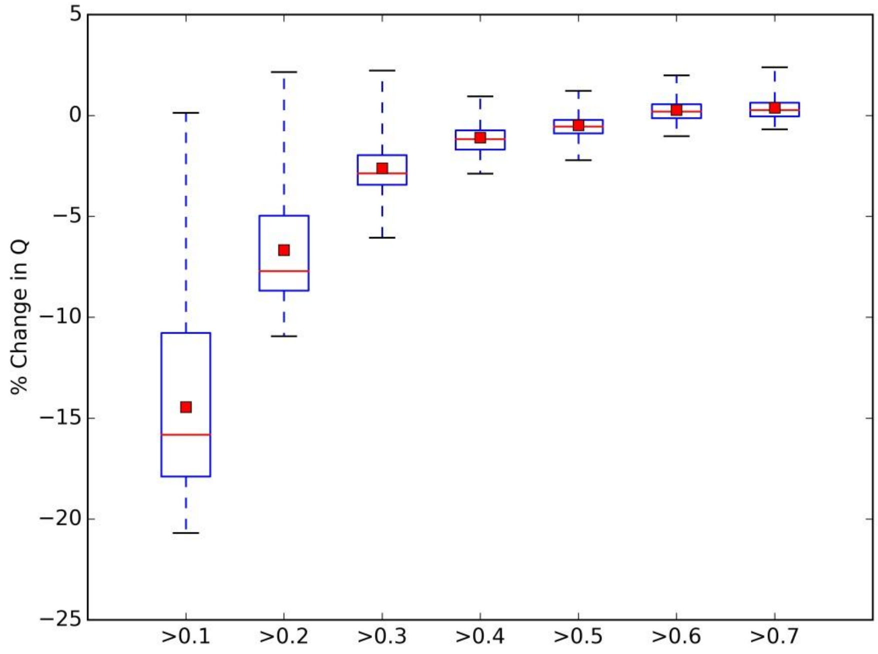

Figure 4.25 MaxQ percentage reduction for the field scale flood risk based aeration scenarios modelling the change assumed heavy compaction levels to light soil compaction levels.

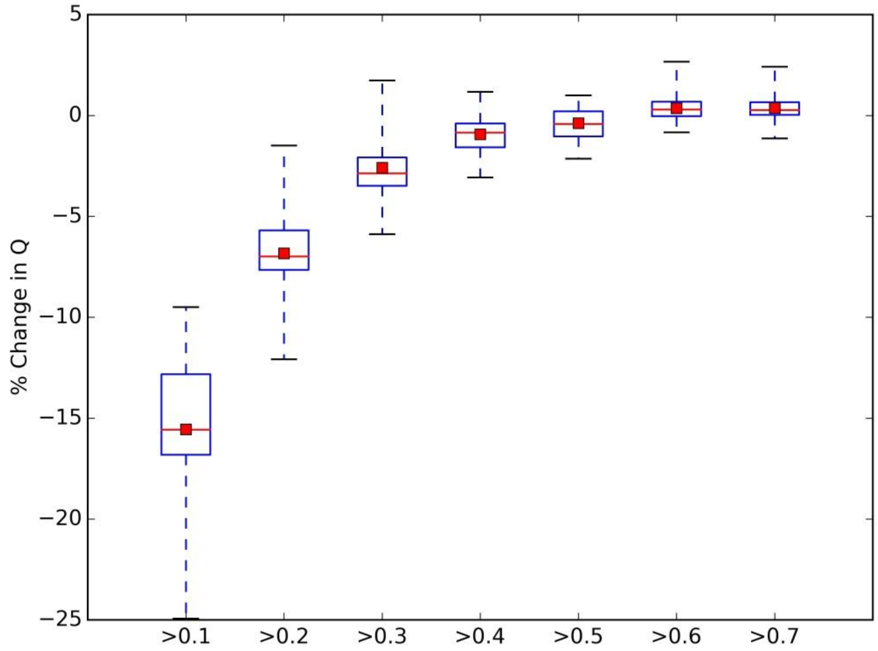

Figure 4.26 MaxQ percentage reduction for the field scale flood risk based aeration scenarios modelling the change assumed heavy compaction levels to medium soil compaction levels.

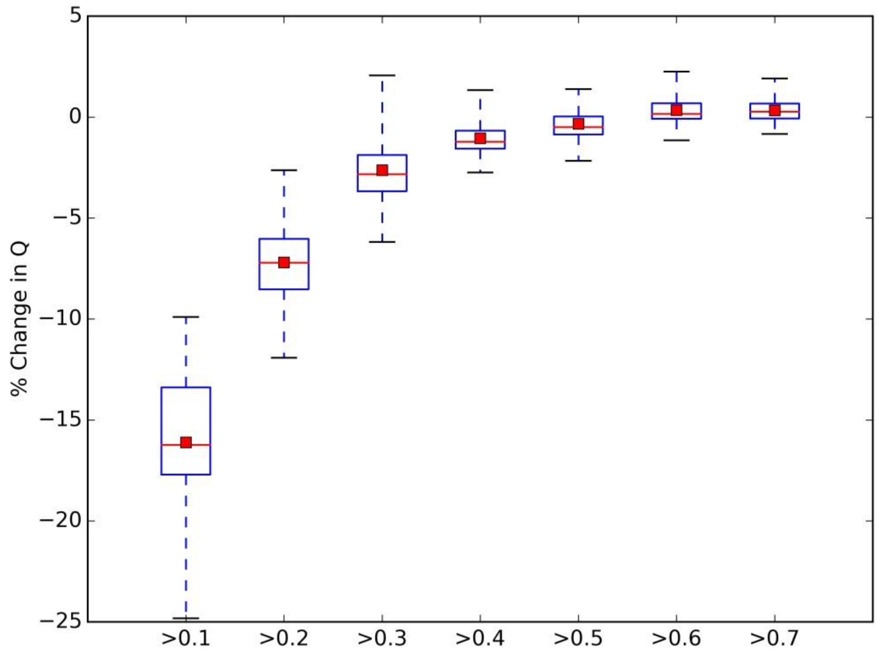

Figure 4.27 MaxQ percentage reduction for the field scale flood risk based aeration scenarios modelling the change assumed medium compaction levels to light soil compaction levels.

The field scale flood risk based aeration scenarios for each of the three compaction alteration sets established a trend of a diminishing MaxQ reduction as the flood risk management technique application area is decreased. The mean MaxQ reduction for the above 0.1, 0.2, 0.3 and 0.4 scenarios ranged from -14.46% to 16.12%, -6.67% to -7.19%, -2.58% to -2.63 and -0.94% to -1.09% respectively. The corresponding median values range from -15.57% to -16.24%, -6.98% to -7.71%, -2.83% to -2.87 and -0.85 to -1.21% accordingly. 28 of the 30 model runs had a MaxQ reduction of greater than 10% percent for the above 0.1 heavy to medium and medium to light compaction level scenarios, with 22 out of 30 for the heavy to light scenario and 25 of the 30 model runs had a decrease in MaxQ of above five percent for the 0.2 scenarios. The three above 0.3 scenarios had 23 of the 30 model runs showing a MaxQ decrease of greater than 2%. The mean and median MaxQ reduction for the above 0.5, 0.6 and 0.7 soil aeration scenarios for the 30 model runs using the three compaction level changes was below -0.5%. This technique is thus not considered a suitable flood risk mitigation solution unless it can be widely adopted.

Outlined in the land cover driven soil aeration scenarios (section 4.4.7.1) the assumed heavy compaction to light compaction level scenarios had the smallest impact on MaxQ reduction for the scenarios with the greatest area coverage of soil aeration. However with the land assigned for soil aeration reduced the impact of aerating the soil from heavy to light compaction levels has, albeit marginally, the greatest reduction in MaxQ. This behaviour was evident using the mean MaxQ reduction from the above 0.3, 0.4 and 0.5 soil aeration scenarios where the increased infiltration capacity and porosity relationship of the heavily and lightly compacted soil (in contrast to the heavy to medium and medium and light compaction levels) is potentially storing more water at the targeted fields.

4.4.8 Large woody debris dam scenarios

Large woody debris (LWD) dams can slow and divert flood discharge onto the surrounding woodland floor and offer an artificial approach to a natural process; they target peak discharge in small ditches and channels and a cumulative approach can reduce peak flood flow (Environment Agency, 2011; Quinn et al., 2013). LWD dams store and attenuate water during high flow events with each LWD dam and surrounding channel and floodplain morphology reacts differently with regards to flow attenuation (Forestry Commission Wales, 2007). There is the possibility to place LWD debris dams at regular intervals in the channel and for extensive reach lengths; Forestry Commission Wales (2007) state a LWD dam can be placed every 7 to 10 channel widths with Nisbet et al. (2011) ascertaining that the channels should not be greater than 5m in width to reduce the risk of failure and washout of debris.

4.4.8.1 Scenario development

LWD debris dams are difficult to represent in a model at a catchment scale due to the complex hydraulic processes involved. They have been represented using CRUM3 through the ability to restrict flow to a set value for selectable channel reaches in the channel network. With this study using a 50m x 50m cell size (representative cell lengths of 50m or 70.7m) the effects of LWD dams was simulated using neighbouring channel cells. With previous research into LWD dams stating that they are best applied to smaller channels it was determined that channels with a Strahler number of 1, 2 and 3 were to have LWD dams applied; the Strahler order numbers for the catchment are shown in Figure 4.28.

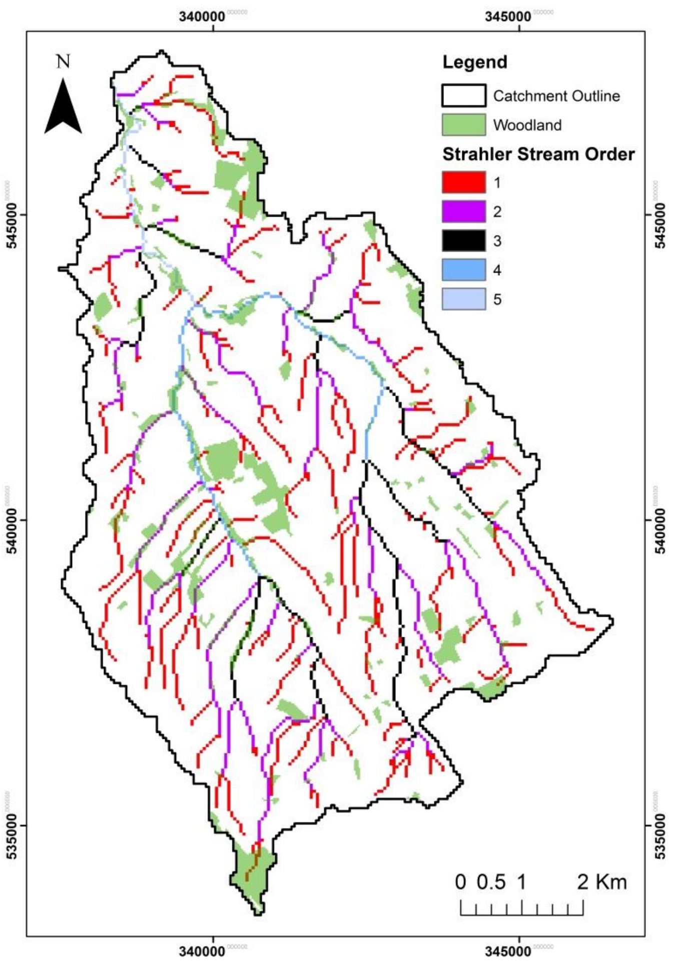

Figure 4.28 The Strahler stream order in the River Roe catchment and the areas of deciduous and coniferous woodland

To define a value simulating the effect of LWD flow restriction to the selected wooded channel reaches the maximum discharge of ten random points for each Strahler number was measured throughout the catchment; this was achieved using a random number generator to select ten reach identification numbers for wooded channel reaches for each Strahler number. The mean of the ten maximum discharge values was taken to create a catchment-wide average maximum discharge for each Strahler value; 1.99m^3s^{-1} for Strahler number 1 channel cells, 4.49m^3s^{-1} for Strahler number 2 channel cells and 5.29m^3s^{-1} for Strahler number 3 channel cells.

The reduction in maximum discharge allowed through a restricted channel reach was calculated using values from Wenzel et al. (2014). Their research found an average peak discharge of -2.2% under LWD conditions with additional peak flow reduction values of -25% and -40% acquired through high flow threshold testing. The three flow reduction percentages were applied to the catchment-wide average maximum discharge values for each Strahler number (Table 4.1).

	Original (m^3s^{-1})	-2.2% (m^3s^{-1})	-25% (m^3s^{-1})	-40% (m^3s^{-1})
Strahler 1	1.99	1.94	1.49	1.19
Strahler 2	4.49	4.39	3.37	2.69
Strahler 3	5.29	5.17	3.97	3.17

Table 4.1 Catchment-wide average maximum discharge created from ten randomly selected wooded channel reaches from the corresponding Strahler number and the restricted maximum discharge flows for each Strahler number using Wenzel et al. (2014).

For each of the three peak flow reduction percentages seven flood risk reduction scenarios were created to represent LWD dams at a catchment scale. Using Strahler numbers these scenarios were all the wooded channel reaches with a Strahler order of 1, 2, 3, 1 and 2, 1 and 3, 2 and 3 and all three values.

4.4.8.2 Large woody debris dams scenario results

The results for simulating LWD dams using the three maximum discharge percentages are shown in Figures 4.29 (-2.2% reduction in maximum discharge), 4.30 (-25% reduction in maximum discharge) and 4.31 (-40% reduction in maximum discharge). For all three scenario sets the implementation of LWD dams in both Strahler 1 and Strahler 2 channel reaches results in an increase in mean and median MaxQ. This is potentially due to the flow restriction prolonging the maximum discharge moving through to the downstream cell where the LWD dams are placed and the cumulative effect at Stockdalewath of prolonged, but restricted, maximum discharge in addition to the unwooded channels is an increase in MaxQ. All three scenario sets with LWD dams on Stahler 3 channels had a reduction in MaxQ; the -2.2% scenario had a mean MaxQ reduction of -1.06% and a median MaxQ reduction of -1.09%, the -25% scenario had a mean reduction of -2.37% and median reduction of -2.91% and the -40% scenario had a mean reduction of -4.33% and a median of -4.61%.

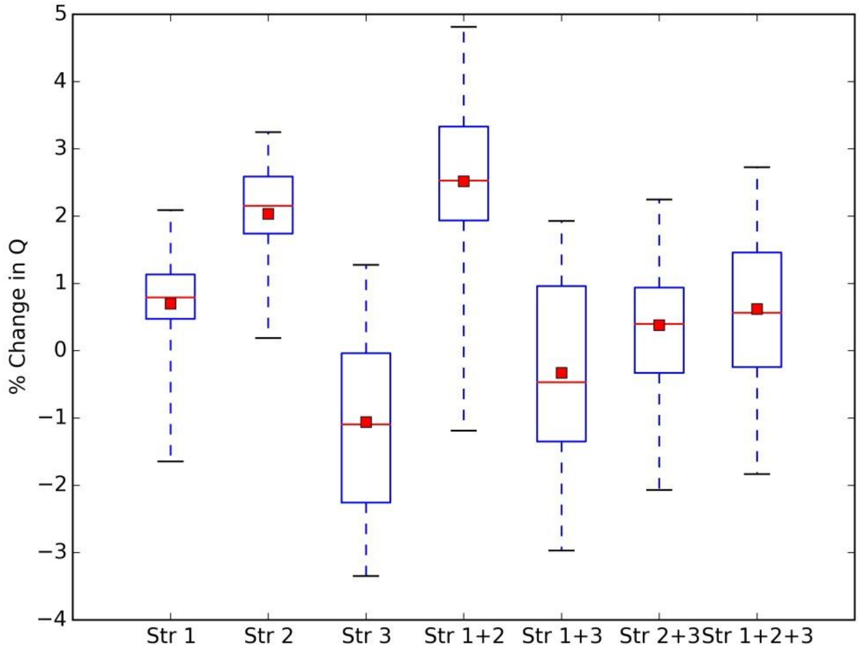

Figure 4.29 LWD dam scenarios for the Strahler number combinations using the -2.2% maximum discharge reduction from Wenzel et al. (2014).

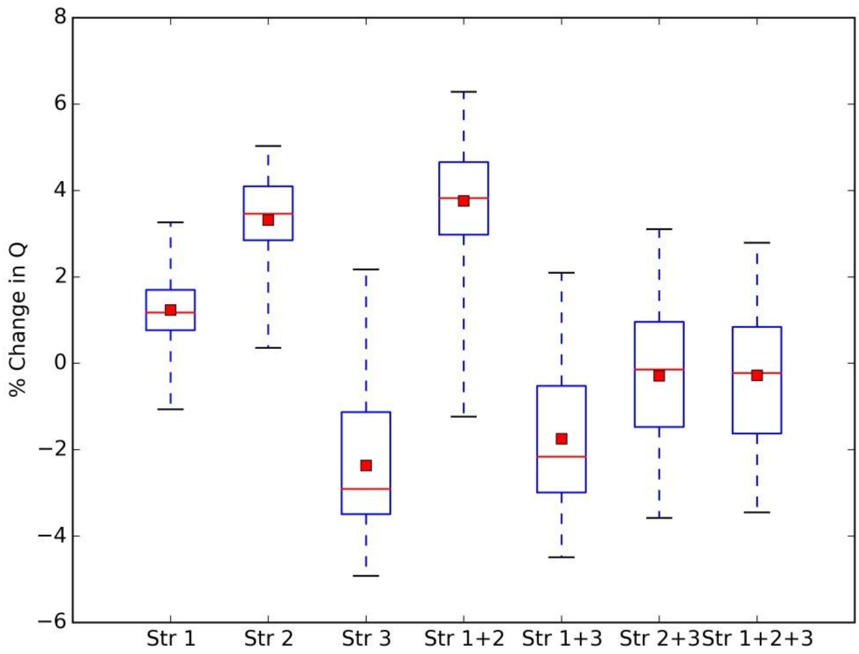

Figure 4.30 LWD dam scenarios for the Strahler number combinations using the -25% maximum discharge reduction from Wenzel et al. (2014).

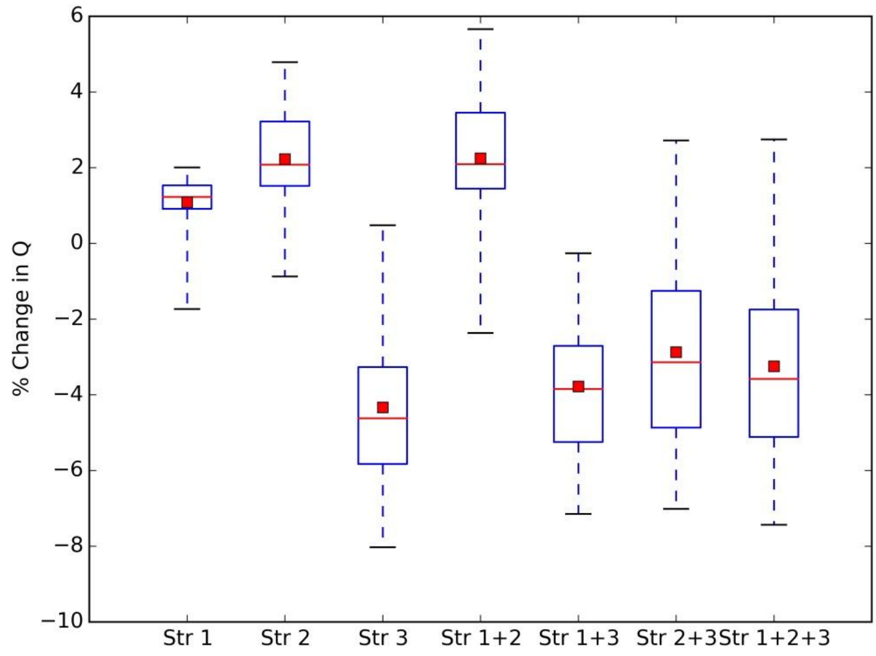

Figure 4.31 LWD dam scenarios for the Strahler number combinations using the -40% maximum discharge reduction from Wenzel et al. (2014).

The use of combinations of Strahler numbers to increase the catchment area under the influence of LWD dams failed to have an increased reduction in MaxQ when compared to the Strahler 3 only LWD dam scenarios. The collective mean and median increase on MaxQ from the Strahler 1 and, in particular, Strahler 2 LWD dams decreased the effectiveness of the Strahler 3 LWD dams at reducing MaxQ. This is highlighted using the difference in mean MaxQ reduction in the Strahler 1 and 3 and Strahler 2 and 3 scenarios; for the -25% scenario the Strahler 1 and 3 scenario had a mean MaxQ reduction of -1.75% and the Strahler 2 and 3 scenario had a -0.28% reduction and the 40% scenario had a corresponding mean MaxQ reduction of -3.78% and -2.87%.

The LWD dam scenario results for all three maximum flow reduction percentages suggest that for the greatest impact on MaxQ and thus for flood risk reduction LWD dams should be concentrated on wooded channel with a Strahler value of 3 for the River Roe catchment. It must be noted that creation of an average maximum discharge for each Strahler value to maximise the simplicity of the scenarios had a potentially significant impact on the MaxQ reduction.

4.5 The impact of natural flood management on the low flow regime in the River Roe catchment

Lows flows are a natural and essential part of a catchments hydrological regime and, with extreme low flows damaging to the local population, ecology, river morphology and agricultural productivity, the impact of the flood risk reduction scenarios in the River Roe catchment on low flows must be considered (Easterling and Mendelsohn, 2000; Environment Agency, 2008; Smith, 2011). This was achieved through the comparison of Q99 low flow statistic from the top 30 model parameter set runs under the existing land cover and with the flood risk reduction scenario applied; Q99 is the flow that is exceeded ninety-nine percent of the time and a reduction in Q99 is considered detrimental. Under existing land cover conditions the mean Q99 was $0.024m^3s^{-1}$, the median Q99 was $0.022m^3s^{-1}$, the maximum Q99 was $0.108m^3s^{-1}$ and the minimum Q99 was $0.003m^3s^{-1}$.

4.5.1 The impact of land cover change based flood risk reduction scenarios on Q99 flow

As with the change in MaxQ, the impact on low flows from the land cover change flood risk reduction scenarios was largest when the greatest amount of land cover was altered. The most extreme positive and negative changes in Q99 were seen with the blanket coverage scenarios. The most significant mean reduction in the low flow regime in the River Roe catchment was under blanket urban land cover (-94.89%); this can be attributed to the soil layer not storing limited water and with a low friction factor there is rapid surface runoff. Both the deciduous woodland and coniferous woodland blanket land cover change scenarios predicted a sizeable reduction in low flow with a mean Q99 reduction of -71.16% and 88.53% respectively. In contrast to the urban land cover change, the woodland land cover scenarios would increase evapotranspiration rates within the catchment and thus reduce the precipitation stored in the soil. Additionally, water reaching the soil layer in woodland land cove scenarios would be stored in a deeper, more porous soil layer than the existing catchment land cover and consequently the water would face a longer travel time route through the dynamic layer. The arable blanket cover scenarios had a mean Q99 decrease of -5.48% whilst the improved grassland and natural grassland blanket land cover change scenarios had a mean Q99 increase of 21.22% and 39.90%. The increase could be the result of blanket grassland coverage increasing the soil moisture and, in turn, increasing the baseflow within the catchment.

Land cover change scenarios implementing deciduous woodland change experienced a reduction in Q99 and conversely those scenarios with areas devoted to natural grassland cover change experienced an increase in Q99. This can be demonstrated with the 25m riparian buffer zone scenario which assigned deciduous woodland land cover change saw a mean Q99 reduction of -34.22% and with natural grassland land cover change had a mean Q99 increase of 17.77%. Another example is made using the field buffer zone above 0.2 scenario in which the 30 models runs had a mean Q99 reduction of -5.98% with deciduous woodland and a Q99 increase of 4.71% using natural grassland.

4.5.2 The impact of soil aeration based flood risk reduction scenarios on Q99 flow

All three soil aeration scenarios had a positive impact on the low flow regime with an increase in Q99 predicted from the top 30 model runs. As with the above land cover change scenarios the greater the area subjected to soil aeration, the larger the increase in Q99; the scenario implementing soil aeration on all the improved grassland and arable land cover had the largest impact on Q99. When the soil compaction level was improved with respect to the adjacent compaction level, there was a mean Q99 increase of 228.92% for the heavy to medium compaction scenario and a mean Q99 increase of 239.32% for the medium to light compaction scenario. The heavy to light compaction scenario for the arable and improved grassland area had a mean increase of 342.74% on Q99; the increase in Q99 in comparison to the other compaction scenarios can be accounted for as the soil is more porous and the water moves vertically through the dynamic layer more rapidly. The disparity between the three compaction layers can be highlighted again using the above 0.2 soil aeration scenario (12.38% catchment area to bed aerated) in which the heavy to medium compaction level scenario (21.77% mean Q99 increase) and medium to light compaction level scenario (22.84% mean Q99 increase) have a noticeably lesser impact that the heavy to light compaction level scenario (47.60%).

4.5.3 The impact of large woody debris dam flood risk reduction scenarios on Q99 flow

Large woody debris dams are designed to attenuate water during a high flow event whilst having no impact on the low flow regime within a catchment; water during low flow conditions is allowed to flow under or through the wooded structure uninhibited (Environment Agency, 2011; Quinn et al., 2013). This minimal impact is predicted in the 30 model runs on CRUM3 with the LWD dam scenarios all having a Q99 reduction of less than -0.06% and a Q99 increase of less than 0.13%. This change in Q99 is a statistical artefact of changing the higher flows within the flow duration curve.

4.6 Summary

This chapter has assessed the effectiveness of a variety of catchment-based land use management techniques and interventions at reducing flood risk; these measures included large scale and spatially targeted land cover change and soil aeration and also woody debris dams. The mean MaxQ reduction for all the modelled scenarios is shown in Table 4.2. The quantification of the flood risk reduction scenarios was achieved by establishing the reduction in maximum discharge (MaxQ) at Stockdalewath, the centre of the 2005 and 2013 flooding. The impact on the catchment low flow regime developed as a consequence of the implemented flood risk reduction scenarios was ascertained to ensure an effective flood risk reducing option would not cause unforeseen issues through alteration of the catchment hydrology. The results presented are explored in the following chapter.

Table 4.2 The mean MaxQ reduction for all the tested scenarios in order of the effectiveness.

Scenario	Mean MaxQ %change from existing catchment land cover
Soil Aeration Med to Low Arable and Improved Grassland	-64.20
Soil Aeration High to Med Arable and Improved Grassland	-63.13
Soil Aeration High to Low Arable and Improved Grassland	-55.47
Soil Aeration Med to Low Improved Grassland	-50.8
Soil Aeration High to Med Improved Grassland	-50.37
Soil Aeration High to Low Improved Grassland	-48.26
Blanket Coverage Deciduous Woodland	-36.36
Hydrological Conductivity >0.5 Deciduous Woodland	-35.38
Hydrological Conductivity >0.6 Deciduous Woodland	-34.71
Hydrological Conductivity >0.7 Deciduous Woodland	-33.19
Hydrological Conductivity >0.8 Deciduous Woodland	-22.98
Soil Aeration Med to Low Arable	-18.54
Soil Aeration High to Med Arable	-17.70
Soil Aeration Med to Low >0.1	-16.11
Soil Aeration High to Med >0.1	-15.55
Blanket Coverage Natural Grassland	-15.24
Soil Aeration High to Low Arable	-14.93
Soil Aeration High to Low >0.1	-14.46
Hydrological Conductivity >0.5 Natural Grassland	-13.90
Hydrological Conductivity >0.6 Natural Grassland	-13.31
Field Coverage >0.1 Deciduous Woodland	-12.09
50m Riparian Buffer Deciduous Woodland	-11.98
Flood Risk Generation >0.1 Deciduous Woodland	-11.65
Hydrological Conductivity >0.7 Natural Grassland	-10.88
Hydrological Conductivity >0.9 Deciduous Woodland	-8.71
Soil Aeration Med to Low >0.2	-7.19
Soil Aeration High to Med >0.2	-6.83
Soil Aeration High to Low >0.2	-6.67
Hydrological Conductivity >0.8 Natural Grassland	-6.17
25m Riparian Buffer Deciduous Woodland	-5.23
Field Buffer >0.1 Deciduous Woodland	-5.08
Field Coverage >0.2 Deciduous Woodland	-4.89
Flood Risk Generation >0.1 Natural Grassland	-4.78
LWD Dams -40% Strahler 3	-4.33
Field Coverage >0.1 Natural Grassland	-4.25
Flood Risk Generation >0.2 Deciduous Woodland	-4.06
LWD Dams -40% Strahler 1 and 3	-3.78
LWD Dams -40% Strahler 1, 2 and 3	-3.24

LWD Dams -40% Strahler 2 and 3	-2.88
Soil Aeration Med to Low >0.3	-2.63
Hydrological Conductivity >0.9 Natural Grassland	-2.62
Soil Aeration High to Low >0.3	-2.61
Soil Aeration High to Med >0.3	-2.59
Flood Risk Generation >0.2 Natural Grassland	-2.57
LWD Dams -25% Strahler 3	-2.37
Field Coverage >0.2 Natural Grassland	-1.97
Field Buffer >0.1 Natural Grassland	-1.96
Flood Risk Generation >0.3 Deciduous Woodland	-1.88
Field Buffer >0.2 Deciduous Woodland	-1.82
LWD Dams -25% Strahler 1 and 3	-1.75
50m Riparian Buffer Natural Grassland	-1.49
Flood Risk Generation >0.3 Natural Grassland	-1.28
Field Coverage >0.3 Deciduous Woodland	-1.10
Soil Aeration High to Low >0.4	-1.10
Flood Risk Generation >0.4 Deciduous Woodland	-1.06
LWD Dams -2.2% Strahler 3	-1.06
Soil Aeration Med to Low >0.4	-1.05
Soil Aeration High to Med >0.4	-0.94
Field Buffer >0.2 Natural Grassland	-0.85
Flood Risk Generation >0.4 Natural Grassland	-0.72
Field Coverage >0.3 Natural Grassland	-0.64
Field Coverage >0.4 Deciduous Woodland	-0.56
Soil Aeration High to Low >0.5	-0.48
25m Riparian Buffer Natural Grassland	-0.47
Soil Aeration High to Med >0.5	-0.39
Flood Risk Generation >0.5 Natural Grassland	-0.36
Soil Aeration Med to Low >0.5	-0.33
LWD Dams -2.2% Strahler 1 and 3	-0.33
Field Buffer >0.3 Natural Grassland	-0.29
LWD Dams -25% Strahler 2 and 3	-0.29
Blanket Coverage Improved Grassland	-0.28
LWD Dams -25% Strahler 1, 2 and 3	-0.28
Field Buffer >0.3 Deciduous Woodland	-0.26
Field Coverage >0.5 Deciduous Woodland	-0.24
Flood Risk Generation >0.6 Natural Grassland	-0.23
Flood Risk Generation >0.5 Deciduous Woodland	-0.22
Flood Risk Generation >0.9 Natural Grassland	-0.21
Flood Risk Generation >0.7 Natural Grassland	-0.2
Flood Risk Generation >0.8 Natural Grassland	-0.18
Field Coverage >0.4 Natural Grassland	-0.12
Field Buffer >0.4 Natural Grassland	-0.06

Field Coverage >0.5 Natural Grassland	-0.05
Field Buffer >0.4 Deciduous Woodland	0.01
Field Buffer >0.6 Natural Grassland	0.02
Field Coverage >0.7 Natural Grassland	0.02
Field Buffer >0.5 Natural Grassland	0.04
Flood Risk Generation >0.9 Deciduous Woodland	0.04
Field Buffer >0.7 Natural Grassland	0.06
Field Coverage >0.6 Natural Grassland	0.06
Field Buffer >0.6 Deciduous Woodland	0.09
Field Buffer >0.5 Deciduous Woodland	0.10
Field Coverage >0.6 Deciduous Woodland	0.10
Flood Risk Generation >0.7 Deciduous Woodland	0.10
Field Coverage >0.7 Deciduous Woodland	0.11
Flood Risk Generation >0.6 Deciduous Woodland	0.11
Flood Risk Generation >0.8 Deciduous Woodland	0.12
Field Buffer >0.7 Deciduous Woodland	0.15
Soil Aeration High to Low >0.6	0.28
Soil Aeration Med to Low >0.7	0.33
Soil Aeration Med to Low >0.6	0.35
Soil Aeration High to Med >0.6	0.36
Soil Aeration High to Med >0.7	0.37
Soil Aeration High to Low >0.7	0.38
LWD Dams -2.2% Strahler 2 and 3	0.38
LWD Dams -2.2% Strahler 1, 2 and 3	0.62
LWD Dams -2.2% Strahler 1	0.70
LWD Dams -40% Strahler 1	1.09
LWD Dams -25% Strahler 1	1.13
LWD Dams -2.2% Strahler 2	2.04
LWD Dams -40% Strahler 2	2.23
LWD Dams -40% Strahler 1 and 2	2.24
LWD Dams -2.2% Strahler 1 and 2	2.52
LWD Dams -25% Strahler 2	3.42
LWD Dams -25% Strahler 1 and 2	3.76
Blanket Coverage Arable	5.37
Blanket Coverage Coniferous Woodland	8.18
Blanket Coverage Urban	48.4

5 Discussion and Conclusion

5.1 Introduction

This aim of this research project was to determine the effectiveness of catchment-based land management techniques and interventions at reducing flood risk in a rural UK catchment. The research was undertaken using stakeholder engagement, SCIMAP-Flood and the CRUM3 hydrological simulation model. The results of the project were presented in the previous chapter and the methodology employed is in chapter 3.

5.2 Discussion

5.2.1 Flood risk reduction through natural flood management in the River Roe catchment

Results demonstrated that soil aeration was the most effective natural flood management technique for flood risk reduction in the River Roe catchment. For the top 30 ranked model runs on CRUM3, the results determined that the more land assigned to soil aeration throughout the catchment the greater the mean and median reduction in MaxQ. The assumed heavy compaction to light compaction level scenarios had, perhaps unexpectedly, the smallest impact on MaxQ reduction. This can be attributed to the soil parameter relationship and the increased difference between the original and aerated soil parameters in comparison to the other two scenario sets. The greatly increased porosity and infiltration capacity of the soil may result in throughflow moving slightly faster through the dynamic layer and hence the smaller reduction in MaxQ. Regardless of the existing and desired soil compaction state, the model results showed a greater impact on MaxQ reduction for the same application area as land cover change. In addition to reducing flood risk, potential aeration had a positive impact on the catchment low flow regime. With the approval of the stakeholders and the possibility of increased agricultural productivity, catchment-wide soil aeration would be the most suitable for reducing flood risk the River Roe catchment.

The most effective land cover categories for MaxQ reduction were deciduous woodland and natural grassland with the greatest achievable mean MaxQ reduction using land cover change of -36.36% using blanket coverage of catchment with deciduous woodland. The feasibility of the land cover change based flood risk reductions scenarios is uncertain and to enable a significant reduction in MaxQ a sizeable proportion of the catchment area would have to be acted on; this could negatively impact on the agricultural practice by reducing the area of productive land in the rural catchment and was a major concern raised by stakeholders. Land cover change scenarios utilising less than five percent of current agriculturally productive land had a limited impact on MaxQ reduction in the River Roe catchment with a less than one percent reduction in MaxQ.

The analysis of LWD dam usage in the River Roe catchment demonstrated that concentrating exclusively on the slightly larger and more connected channels, those with a Strahler value of 3, was the most efficient flood risk reduction scenario. Dependent on which discharge reduction percentage is used from Wenzel et al. (2014) the MaxQ reduction was between -1.06% and -4.33%. For all three percentage reductions (-2.2%, -25% and -40%) the implementation of large woody debris dams in both Strahler 1 and Strahler 2 channel reaches results in an increase in mean and median maximum river flow. This is potentially due to the flow restriction prolonging the maximum discharge moving through to the downstream cell where the large woody debris dams are placed. The cumulative effect at Stockdalewath of prolonged, but restricted, maximum discharge in addition to the unwooded channels is a slight increase in maximum river flow.

5.2.2 Implementing catchment-based natural flood management techniques and interventions without constraints

Throughout this research, potential constraints on applying a given flood risk reduction scenario have been considered; the majority of these arose during stakeholder engagement. From the results of the stakeholder engagement there were issues made apparent involving the size of the area devoted to land cover change and the subsequent loss of catchment agricultural productivity; scenarios such as LWD dams in wooded tributaries were designed to combat these concerns. It should be noted that no landowners within the catchment were able to attend the stakeholder engagement exercises however residents within the catchment determined the need for incentives to get existing land owners to enact flood risk natural flood management techniques and interventions on their land; land owners were predicted to have varying reactions to the proposed implementation of changes to their property. Finally there were constraints through the impact of the flood risk reduction scenarios on the catchment low flows; the low flow regime is essential and could not be discarded for the exclusive consideration of maximum discharge reduction.

Without the need to consider these constraints with regards to scenario feasibility it was evident in the project findings that maximising the area assigned to the application of land cover change and soil aeration had a significant increase in the levels of flood risk reduction. The return of the River Roe catchment to the a fully forested state, replicating its condition when it formed part of the Forest of Inglewood in the medieval period, would provide the necessary reduction in maximum discharge for long term mitigation of flooding events. This large scale afforestation could be applied to the majority of at-risk rural catchments in the UK with many previously being fully forested. Continuous soil aeration implementation on arable and improved grassland land cover at the catchment scale to keep soil compaction levels consistently low would be another preferred solution to flood risk reduction; however farmers face time, weather and financial constraints and despite a potential increase in productivity many are not capable of enacting soil aeration at the required scale.

5.2.3 Implementing natural flood management techniques and interventions with consideration to the loss of agriculturally productive land

Giving consideration to the agriculturally productive land (arable land and improved grassland) in the catchment was an issue raised by the catchment stakeholders. The natural flood management techniques and interventions that were most effective if implemented on around 20%, 10%, 5% and 2% of the catchments agricultural area, are detailed below; scenarios using greater than 20% of the agricultural land in the catchment would be very unlikely to be implemented based from stakeholder feedback and were not considered. A ratio of the percentage reduction in maximum discharge and the area of agricultural land affected for each of the scenarios below are shown for each section in Table 5.1 (20% of catchment agricultural area), Table 5.2 (10%), Table 5.3 (5%) and Table 5.4 (2%). The ratio indicates the MaxQ reduction value of each unit area of agriculturally productive land affected under the given scenario.

Flood Risk Reduction Scenario	MaxQ reduction (%)	Agricultural land affected (%)	Ratio (% reduction : % agricultural land)
50m riparian buffer (deciduous woodland)	-11.98	21.21	0.57
Field buffer >0.1 (deciduous woodland)	-5.08	17.62	0.29
Field land cover change >0.2 (deciduous woodland)	-4.89	14.52	0.34
Soil aeration >0.2	-6.67 to -7.19	14.52	0.46 to 0.50

Table 5.1 A table showing the ratio of the percentage reduction in maximum river flow and the percentage of agriculturally productive land affected by the flood risk reduction scenario for the scenarios using around 20% agriculturally productive land.

Flood Risk Reduction Scenario	MaxQ reduction (%)	Agricultural land affected (%)	Ratio (% reduction : % agricultural land)
25m riparian buffer (deciduous woodland)	-5.23	11.10	0.47
Field buffer >0.2 (deciduous woodland)	-1.82	8.23	0.22
Field land cover change >0.3 (deciduous woodland)	-1.10	7.02	0.16
Soil aeration >0.3	-2.59 to -2.63	7.02	0.37

Table 5.2 A table showing the ratio of the percentage reduction in maximum river flow and the percentage of agriculturally productive land affected by the flood risk reduction scenario for the scenarios using around 10% agriculturally productive land.

Flood Risk Reduction Scenario	MaxQ reduction (%)	Agricultural land affected (%)	Ratio (% reduction : % agricultural land)
Field buffer >0.3 (deciduous woodland)	-0.26	4.23	0.06
Field land cover change >0.4 (deciduous woodland)	-0.56	2.89	0.19
Soil aeration >0.4	-0.94 to -1.10	2.89	0.33 to 0.38

Table 5.3 A table showing the ratio of the percentage reduction in maximum river flow and the percentage of agriculturally productive land affected by the flood risk reduction scenario for the scenarios using around 5% agriculturally productive land.

Flood Risk Reduction Scenario	MaxQ reduction (%)	Agricultural land affected (%)	Ratio (% reduction : % agricultural land)
Field buffer >0.4 (deciduous woodland)	-0.06	1.81	0.03
Field land cover change >0.5 (deciduous woodland)	-0.24	1.34	0.18
Soil aeration >0.5	-0.33 to -0.48	1.34	0.25 to 0.36
LWD dams (Strahler order of 3)	-1.06 to -4.33	0	No agricultural land affected

Table 5.4 A table showing the ratio of the percentage reduction in maximum river flow and the percentage of agriculturally productive land affected by the flood risk reduction scenario for the scenarios using around 2% agriculturally productive land.

The comparison of the resultant ratios for the selected scenarios illustrates that the most effective natural flood management scenario with regards to maximum discharge reduction and the amount of agriculturally productive land affected was the implementation of 50m riparian buffer zones (0.57). Soil aeration was the most effective of the field based natural flood management scenarios, in comparison to field buffers and field land cover change, whilst the implementation of large woody debris dams did not impact on agriculturally productive land. The results also determine that the use of more agriculturally productive land in a flood risk reduction scenario produced a greater reduction in MaxQ per unit affected. This can be exampled using soil aeration whereby implementation on fields with a flood risk reduction value of greater than 0.2 had a ratio of 0.46 to 0.50 whilst implementation on fields with a value of above 0.5 had a ratio of 0.25 to 0.36; the reduction was evident in all the scenario categories modelled.

5.2.4 Implications of this research for other UK rural catchments at risk of flooding

Natural flood management is a growing option in the UK with regards to helping reduce flood risk at a catchment scale. This research moves towards the creation of a scenario development process that can be applied to rural catchments; using stakeholder engagement and a variety of natural flood management techniques and interventions to assess flood risk reduction effectiveness using a hydrological model. With many of the rural catchments failing to meet central funding criteria this approach offers a way to quantify effectiveness of cheaper natural flood management measures; the quantification vital for consent from governmental organisations such as the Environment Agency.

This study has shown the necessity to involve stakeholders in the development process with the range of stakeholders helping raise concerns and enabling those involved to promote different natural flood management options; they provided an insight into anticipated responses from landowners and farmers within the catchment. The response from individual landowners within a catchment will vary; some landowners will be more amenable to setting aside more land for afforestation or be willing to aerate the soil at more regular intervals and it would be possible to develop flood risk reductions scenarios aiming to incorporate more of their land. One way to encourage a greater uptake and to reduce the need to rely on the preferences of an individual landowner to implement natural flood management measures on their land would be to provide financial incentives; this could be through an extension of the existing Environmental Stewardship agri-environmental scheme run by DEFRA in the UK which, at present, predominantly focuses on environmental benefits such as habitat creation/restoration (Natural England, 2012). Natural flood management measures such as riparian woodland planting or buffer strips are already included within the Environmental Stewardship scheme but, perhaps through the existing points based system, a greater weighting could be given to those within areas identified as suitable for flood risk reduction.

With no landowners within the River Roe catchment present at the stakeholder engagement exercises it is difficult to example the differing responses to the implementation of natural flood management and how it would shape the development of the flood risk reduction scenarios. The local stakeholders also confirmed, through local knowledge, the accuracy of areas highlighted as high risk using SCIMAP-Flood helping verify the science applied to the catchment. The use of stakeholder engagement to establish the maximum area that natural flood management techniques and interventions can be applied with the greater the catchment area assigned for the flood risk reduction measures the greater the increase in the reduction in maximum discharge.

The findings of the project showed certain scenarios that should be trialled at other catchments, but also scenarios that were less effective at reducing flood risk. A rural catchment with limited arable and improved grassland land cover or landowners open to large scale land cover change to reduce flood risk should have targeted afforestation with deciduous woodland applied; minimal land cover change had a limited impact on reducing peak discharge during a flood event. With rural areas predominantly relying on agricultural productivity, the positive impact of catchment scale soil aeration on flood risk reduction and with no land cover change would suggest it should be the first set of scenarios to be assessed. Additionally large woody debris dams have limited or no impact on the extent of agriculturally productive land and would be the next natural flood management intervention to be modelled. Lastly, catchment scale land cover change with deciduous woodland, if agreeable with the relevant catchment landowners, should be simulated with scenarios initially concentrating on the fringes of agricultural land such as riparian buffer zones and field scale buffer zones.

Finally the physical implementation of the most effective scenarios in the River Roe catchment has the potential to be utilised as a case study for other at-risk rural catchments. The results from the CRUM3 hydrological modelling process can be compared to a future flood event in the River Roe catchment and be used to determine the usefulness of the applying the investigated process elsewhere in the UK.

5.2.5 Predicting the impact of natural flood management techniques and interventions using a hydrological model

One of the objectives of this research was to determine whether the impacts of natural flood management at a catchment scale could be quantified using a hydrological model. CRUM3, a spatially distributed hydrological model, was selected as the model to be used having been applied to previous investigations on land management and catchment hydrology. After completing sensitivity analysis, the GLUE experiments and existing land cover weighting, a simulation of the existing catchment hydrological regime was created. Using the flood risk reduction scenarios discussed in chapter 3, with the results in chapter 4, it was apparent that the model could predict the impact of flood reduction measures on both high and low flows and allow for a comparison to the existing catchment conditions.

5.3 Implications arising from this research

5.3.1 Impacts of natural flood management interventions to reduce flood risk

It was evident when conducting a review of the literature for this project that the majority of the research undertaken on natural flood management had been field based with interventions constructed and implemented in trial catchments such as Belford (Wilkinson et al., 2010) and Pickering (Forestry Commission, 2004). The effectiveness of the natural flood management interventions at storing and attenuating flood water in the reviewed research was visually evidenced however there was a lack of quantification of the impact on flood risk reduction. The variation in spatial extent and intensity of rainfall events and catchment conditions is a potential issue for the quantification of flood risk reduction in field based research as for the ideal comparison into the effectiveness of natural flood management interventions the initial conditions would be the same.

The use of a hydrological model in this research allows for the quantification and thus direct comparison of the impact of natural flood management techniques and interventions on flood risk reduction with the same rainfall event. A comparison of the results of the research process can determine the most effective locations and spatial extent for interventions and techniques to be employed without catchment scale field studies having to be enacted.

5.3.2 Methods to determine which natural flood management intervention to use and where to locate them

There has been previous research looking at possible areas where interventions can be made to reduce flood risk with a catchment. An example of this is the Scottish Environmental Protection Agency (SEPA) (2013) initiative ‘Identifying opportunities for natural flood management’ which determines, through slope, land cover, rainfall and soil characteristics, areas in which floodplain storage and runoff reductions measures could be implemented; specific measures are not suggested with large areas being suitable throughout Scotland. An approach, such as that achieved by SEPA, is comparable to the initial SCIMAP-Flood analysis of the catchment used in this project; identifying areas of high connectivity and flood risk generation without considering the opinions of local stakeholders and the potential impact upon the local population.

This study builds upon the preliminary analysis from SCIMAP-Flood with an interdisciplinary approach that uses stakeholder knowledge to coproduce a series of possible natural flood management scenarios to reduce flood risk in a rural catchment. This allows the local stakeholders to raise potential concerns with the implementation of a specific intervention or the use of a certain location within the catchment. The simulation of the coproduced flood risk reduction scenarios on CRUM3 and the subsequent quantification of effectiveness ensured that scenarios created with stakeholder input had a positive impact on reducing the maximum discharge within the catchment.

5.3.3 Role of coproduction of scenarios for natural flood management interventions

The involvement of the catchment stakeholders in the coproduction of natural flood management scenarios altered the emphasis of what an effective solution to reducing flood risk in the catchment would include. Without a participatory approach and the subsequent application of indigenous knowledge the research would have relied upon the results generated from SCIMAP-Flood and would have concentrated on scenario develop using catchment scale natural flood management interventions targeting areas of high connectivity. This approach would have been effective with regards to flood risk reduction and the large scale afforestation using deciduous woodland within the catchment had a significant impact on reduction the maximum discharge during a high flow event.

A major concern raised through the stakeholder engagement element of this study was the area of agricultural land that the landowner could be persuaded to devote to land cover change for flood risk reduction purposes; there was a preference for flood risk reduction solutions that altered minimal agricultural land and it would not have been viable to implement large scale afforestation without a significant impact on the local population. As mentioned in Section 5.2.4, there is the potential, through financial incentives and a possible extension to the DEFRA Environmental Stewardship scheme, to promote the uptake of natural flood management measures. Increased uptake by landowners of natural flood management measures would allow land cover change to be an implementable option within a catchment. Without wide scale acceptance of natural flood management measures the consequent scenarios developed with the input of the catchment stakeholders looked at interventions such as riparian buffer zones and large woody debris dams; these areas tend to be outside of the agriculturally productive zone. Soil aeration, due to the positive impact on agricultural productivity, was suggested as an alternative solution to land cover change that could be implemented on a large scale.

The involvement of the catchment stakeholders in the flood risk reduction scenario development ensured that the solution developed had the approval of the stakeholders and also had been modelled to quantify its effectiveness at reducing the maximum discharge and thus making sure that implementing the scenario was viable.

5.4 Recommendations for future work

Due to time constraints there were potential areas of further research that could be carried out to enhance and develop this project. The soil compaction values were taken from literature derived for another basin area within the Eden catchment. It would have been desirable for saturated conductivity, soil porosity and dynamic layer depth values to have been recorded throughout the River Roe catchment, however with variation within an individual field it would have been difficult to categorise the entire catchment efficiently. The spatial extent of each of the soil compaction categories would have reduced the reliance on assumption that an area was at a consistent compaction level prior to applying soil aeration. The reaction of the soil parameters throughout the catchment to aeration equipment again could have improved the model predictions.

As with the soil compaction parameters, the land cover parameters were also derived from previously published research literature. Again these could be measured throughout the catchment and location specific parameters applied to the model. The LCM2007 land cover categories, in particular deciduous woodland and arable, could be broken down into smaller categories; there is a disparity between soil and vegetation parameters between different crops and trees. The seasonality of the vegetation, including crop planting patterns, could have been fully investigated with different parameters utilised in different seasons.

Finally processes within the catchment occur on a scale that CRUM3 cannot represent; these could have an impact on the hydrological regime. Using a 50m x 50m cell size fails to represent features such as roads, hedgerows, buildings and, perhaps most significantly, land drainage systems. Within agricultural areas land drainage can have an influence on the catchment hydrology (Robinson, 1990; Jones, 1997). It would require a separate modelling study to assess the impact of land drain removal and blockage on the River Roe catchment.

5.5 Conclusion

This study determined that a physically based, spatially distributed hydrological model can be applied to model natural flood management techniques and interventions and quantify the corresponding impact on catchment hydrology in a rural catchment. The hydrological model CRUM3 was used to assess the effectiveness of a variety of flood risk reduction scenarios in the River Roe catchment; these scenarios included spatially targeted land cover change to attenuate overland flow, soil aeration to mitigate soil compaction issues commonly associated with rural catchments and woody debris dams to slow the delivery of water downstream. Catchment stakeholders were engaged to help develop the flood risk reduction scenarios; they provided an insight into anticipated reactions of the wider catchment population to specific measures and applied indigenous knowledge to verify and locate potential locations for measures to be employed. It was established through the research that a significant proportion of land has to be acted upon to have a noticeable reduction in the maximum discharge produced during a flood event; as a consequence of this large scale soil aeration to keep soil compaction to low levels throughout the catchment is arguably the most useful natural flood management measure. Soil aeration produced the greatest reduction in maximum discharge of up to -64.20% and had a positive impact on the catchment low flow regime; additionally would provide a benefit to the agricultural productivity that is essential for implementation in a rural catchment. The second and third most effective scenarios involved catchment wide land cover change using deciduous woodland and natural grassland and had a maximum discharge reduction of -36.36% and 15.24% respectively. The findings of this research could be applied to similar catchments dominated by surface water flooding to find effective solutions to mitigate flood risk.

6 Reference List

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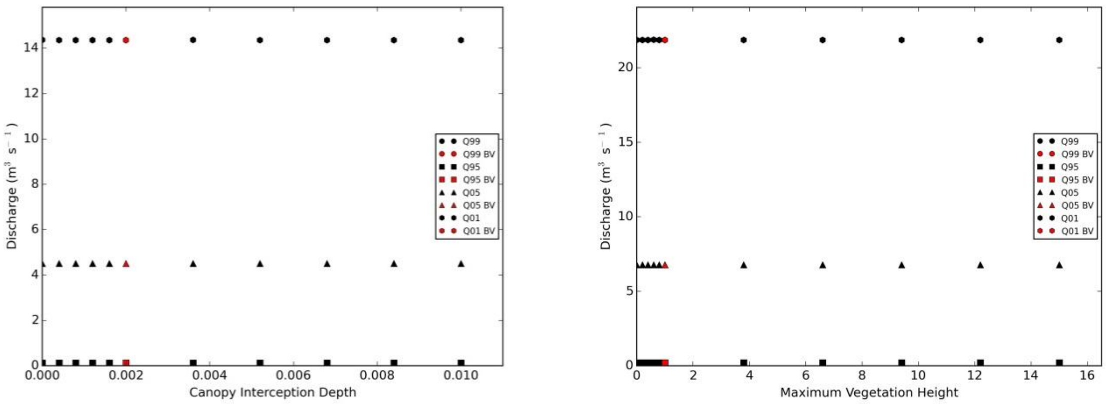
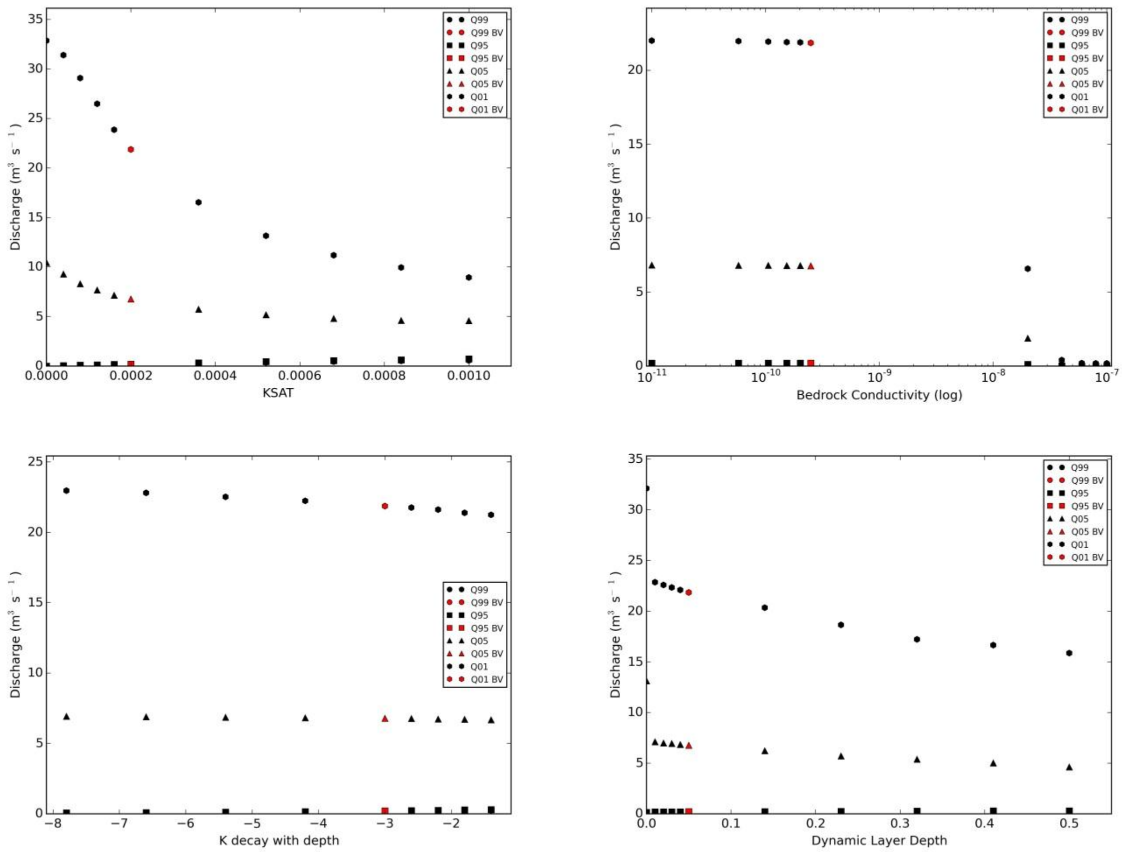
7 Appendices



Appendix A Response of Q01, Q05, Q95 and Q99 discharge change for the two least sensitive parameters sets. (a) Canopy Interception Depth and (b) Maximum Vegetation Height



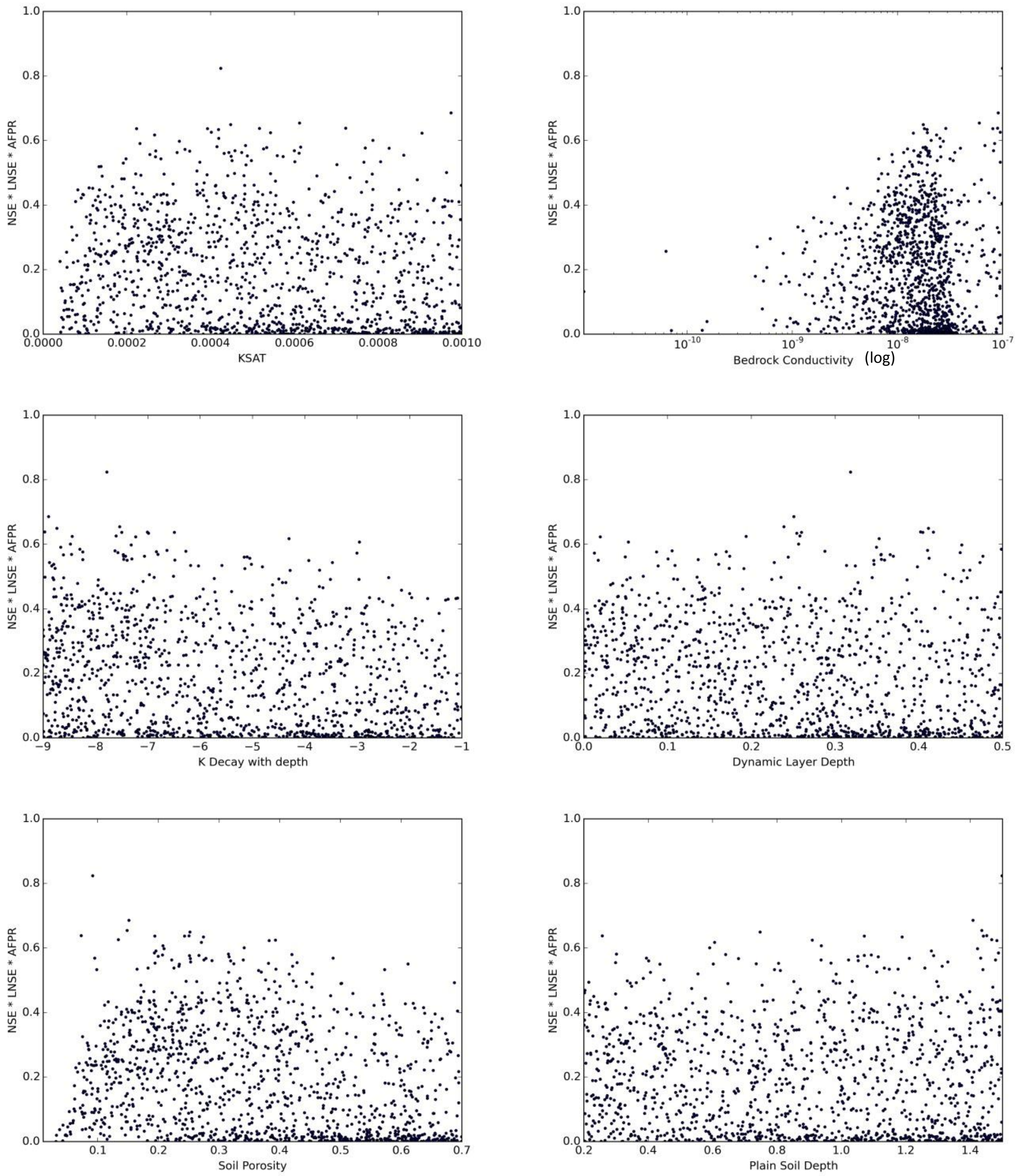
Appendix B Response of Q01, Q05, Q95 and Q99 discharge change for the four most sensitive parameters sets. (a) Saturated Conductivity (Ksat) (b) Bedrock Conductivity (c) K decay with depth and (d) Dynamic Layer Depth

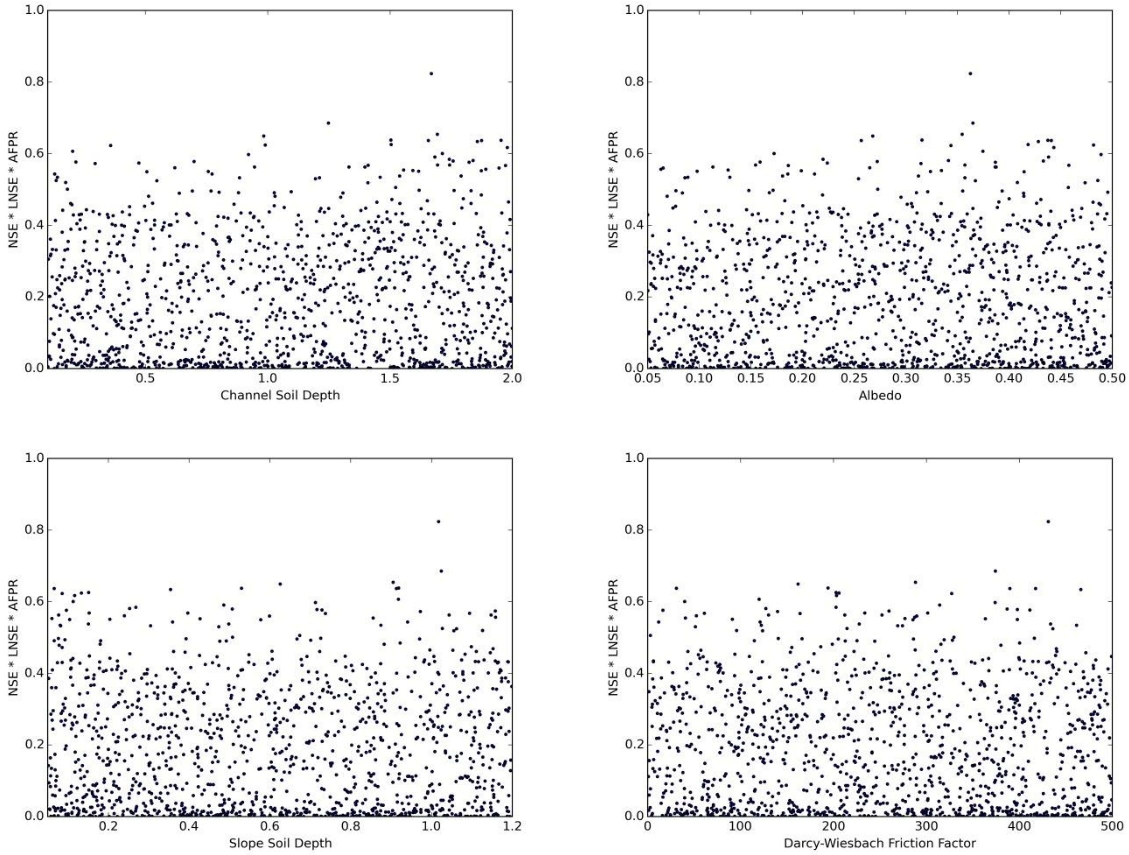
GLUE Rank	Model Run	NSE	NSE Scaled	LNSE	LNSE Scaled	AFPR	AFPR Scaled	NSE * LNSE * AFPR
1	3866	0.593	0.864	0.818	0.970	0.982	0.982	**0.823**
2	774	0.686	1.000	0.775	0.920	0.754	0.745	**0.685**
3	540	0.569	0.829	0.711	0.843	0.937	0.935	**0.654**
4	3523	0.604	0.881	0.689	0.817	0.906	0.903	**0.649**
5	321	0.466	0.679	0.843	1.000	0.941	0.939	**0.638**
6	2331	0.643	0.937	0.623	0.738	0.924	0.921	**0.637**
7	3696	0.535	0.779	0.699	0.829	0.987	0.987	**0.637**
8	4343	0.561	0.817	0.691	0.819	0.952	0.951	**0.636**
9	1219	0.570	0.830	0.704	0.835	0.916	0.914	**0.633**
10	3418	0.480	0.699	0.795	0.943	0.950	0.949	**0.625**
11	4944	0.599	0.873	0.710	0.842	0.854	0.849	**0.624**
12	1856	0.522	0.761	0.795	0.943	0.872	0.868	**0.622**
13	382	0.555	0.808	0.685	0.812	0.941	0.939	**0.617**
14	4993	0.613	0.893	0.578	0.685	0.992	0.991	**0.606**
15	3224	0.617	0.898	0.695	0.824	0.817	0.811	**0.600**
16	3313	0.597	0.870	0.651	0.772	0.893	0.890	**0.598**
17	2579	0.607	0.884	0.623	0.738	0.908	0.905	**0.591**
18	862	0.665	0.969	0.703	0.834	0.732	0.723	**0.584**
19	3118	0.656	0.955	0.657	0.779	0.788	0.781	**0.581**
20	2219	0.559	0.815	0.659	0.782	0.913	0.910	**0.579**
21	3575	0.513	0.747	0.653	0.774	0.999	1.000	**0.578**
22	2720	0.557	0.812	0.688	0.816	0.874	0.870	**0.576**
23	3009	0.493	0.718	0.691	0.820	0.979	0.979	**0.576**
24	4150	0.543	0.790	0.679	0.805	0.905	0.901	**0.574**
25	1974	0.634	0.924	0.611	0.725	0.860	0.855	**0.573**
26	316	0.509	0.741	0.685	0.813	0.945	0.943	**0.568**
27	634	0.428	0.624	0.826	0.980	0.932	0.930	**0.568**
28	109	0.616	0.897	0.636	0.755	0.844	0.839	**0.568**
29	2363	0.541	0.789	0.612	0.725	0.990	0.990	**0.566**
30	3360	0.555	0.808	0.661	0.784	0.891	0.888	**0.563**

Appendix C Performance measures of the top 30 ranked GLUE model parameter sets.

Rank	KSAT	Bedrock Conductivity	K Decay with depth	Dynamic Layer Depth	Soil Porosity	Plain Soil Depth	Slope Soil Depth	Albedo	Channel Soil Depth	DW Friction Factor
1	0.00042	9.98E-08	-7.783	0.319	0.092	1.498	1.018	0.362	1.669	431.168
2	0.00097	9.10E-08	-8.896	0.251	0.152	1.408	1.024	0.365	1.249	374.155
3	0.00061	6.03E-08	-7.536	0.239	0.148	1.436	0.905	0.355	1.694	288.316
4	0.00045	1.76E-08	-8.737	0.412	0.252	0.747	0.626	0.268	0.984	161.861
5	0.00072	8.95E-08	-8.968	0.402	0.073	1.451	0.919	0.316	1.504	194.172
6	0.00052	2.89E-08	-7.010	0.417	0.250	0.258	0.530	0.438	1.954	31.077
7	0.00039	8.08E-08	-7.499	0.260	0.194	1.440	0.066	0.441	1.874	417.563
8	0.00022	1.81E-08	-6.490	0.405	0.243	1.071	0.913	0.257	1.657	389.744
9	0.00042	1.92E-08	-6.987	0.254	0.274	1.188	0.354	0.428	1.857	466.243
10	0.0004	9.51E-08	-7.604	0.258	0.134	1.466	0.152	0.419	1.504	202.640
11	0.00054	1.93E-08	-8.444	0.194	0.393	0.909	0.133	0.482	0.990	205.860
12	0.00091	1.42E-08	-7.232	0.020	0.383	1.482	0.086	0.344	0.358	327.159
13	0.00027	2.36E-08	-4.302	0.353	0.271	0.606	0.116	0.443	1.980	203.178
14	0.00042	2.54E-08	-2.958	0.053	0.207	0.938	0.918	0.375	0.202	119.904
15	0.00079	2.10E-08	-8.479	0.256	0.341	0.591	0.113	0.172	1.714	39.769
16	0.00033	2.73E-08	-7.319	0.451	0.209	1.422	0.712	0.489	0.922	373.910
17	0.00023	8.40E-08	-8.664	0.349	0.196	1.279	0.486	0.438	1.683	314.361
18	0.00048	6.80E-08	-8.297	0.499	0.193	1.487	0.268	0.220	1.742	202.827
19	0.00042	2.57E-08	-6.632	0.411	0.315	0.301	0.253	0.341	1.839	127.143
20	0.00062	1.84E-08	-7.629	0.105	0.420	0.641	0.507	0.433	1.758	386.781
21	0.00053	1.75E-08	-6.271	0.288	0.207	1.093	0.717	0.272	0.698	397.975
22	0.00077	1.89E-08	-6.836	0.170	0.267	1.071	0.729	0.159	0.215	411.236
23	0.00083	3.98E-08	-8.241	0.087	0.251	1.286	0.097	0.387	1.823	16.519
24	0.00053	1.25E-08	-7.570	0.449	0.200	1.051	1.158	0.224	0.473	259.740
25	0.00034	1.86E-08	-3.005	0.013	0.316	1.114	0.972	0.315	0.294	139.697
26	0.00046	1.43E-08	-6.804	0.158	0.488	0.394	0.397	0.154	1.694	301.436
27	0.0006	8.19E-08	-8.459	0.355	0.095	1.432	0.153	0.357	1.743	233.763
28	0.00027	1.94E-08	-7.467	0.366	0.278	1.210	1.094	0.458	1.410	61.130
29	0.00035	2.01E-08	-8.613	0.355	0.253	0.680	0.737	0.186	1.972	164.118
30	0.00047	1.66E-08	-7.423	0.174	0.340	0.936	1.147	0.386	1.397	212.082

Appendix D Parameter values for the top 30 ranked GLUE model runs.


NSE * LNSE * AFPR
KSAT
Bedrock Conductivity (log)
K Decay with depth
Dynamic Layer Depth
Soil Porosity
Plain Soil Depth



Appendix E Dotty plots of the GLUE model performance. (a) Saturated conductivity, (b) Bedrock conductivity, (c) K decay with depth, (d) Dynamic layer depth, (e) Soil porosity, (f) Plain soil depth, (g) Channel soil depth, (h) Albedo, (i) Slope soil depth and (j) Darcy-Weisbach friction factor.